Executive Summary Report to the Michigan State Legislature and Steering Committee

regarding the

16-ft Wide Mobile Home Study

Report No. UMTRI-92-18-1
(Volume 1)

C. MacAdam
F. Streff
C. Christoff
S. Karamihas

May 15, 1992

UMTRI The University of Michigan Transportation Research Institute

Executive Summary Report to the Michigan State Legislature and Steering Committee

regarding the

16-ft Wide Mobile Home Study

Prepared in Cooperation with
The U.S. Department of Transportation
Federal Highway Administration
and
Michigan Department of Transportation
By

The University of Michigan
Transportation Research Institute

Report No. UMTRI-92-18-1

(Volume 1)

C. MacAdam
F. Streff
C. Christoff
S. Karamihas

May 15, 1992

Amount Printed: 40 Total Cost: $84.96 Per Copy: $2.12

Technical Report Documentation Page

1. Report No. FHWA-MI-RD-92-03 UMTRI-92-18-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Executive Summary Report to the Michigan State Legislature and Steering Committee Regarding the 16-ft Wide Mobile Home Study (Volume 1)		5. Report Date May 15, 1992 6. Performing Organization Code
7. Author(s) C. MacAdam, F. Streff, C. Christoff, and S. Karamihas		8. Performing Organization Report No. UMTRI-92-18-1
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road, Ann Arbor, Michigan 48109		10. Work Unit No. (TRAIS) 11. Contract or Grant No. MDOT 91-1291
12. Sponsoring Agency Name and Address Michigan Department of Transportation Lansing, Michigan		13. Type of Report and Period Covered Final 9/12/91 - 5/15/92 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This document represents the final reporting of findings from a study of 16-foot wide mobile homes by the University of Michigan Transportation Research Institute on behalf of its sponsors, the Michigan State Legislature and its intermediary steering committee comprised of representatives from the Michigan Department of Transportation, the Michigan Department of Commerce, the Michigan State Police, and the manufactured housing industry. A primary purpose of the study is to evaluate "the mobility, turning ability, and transporting of mobile homes that are more than 14-1/3 feet wide..." as described in Section 10 of Senate Bill No. 142 from the regular session of the 1991 Michigan State Legislature. The study is focused on issues specifically related to differential effects that mobile home width (i.e., 16-ft widths versus 14-ft widths) may have on adjoining traffic and maneuverability. Recommendations are offered regarding safe operation and allowed access to state highways for such vehicles.

The study relies on both *field data,* collected this past October and November on Michigan highways to evaluate driver behavior in the presence of mobile homes, and *computer analysis* to evaluate the low-speed maneuverability of mobile homes as well as their highway-speed dynamic characteristics.

17. Key Words mobile home, offtracking, encroachment, highway design, wide load, vehicle width, modular home, highway use, crosswind, maneuverability, traffic, mobility, braking, dynamics, stability, hitch, videotape, wind		18. Distribution Statement No restrictions	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 25	22. Price

Table of Contents

1.0 Introduction

This Executive Summary (Volume 1) contains the conclusions and recommendations from a study (contained in total in Volume 2) of 16-foot wide mobile homes by the University of Michigan Transportation Research Institute on behalf of its sponsors, the Michigan State Legislature and its intermediary steering committee comprised of representatives from the Michigan Department of Transportation, the Michigan Department of Commerce, the Michigan State Police, and the manufactured housing industry. A primary purpose of the study was to evaluate "the mobility, turning ability, and transporting of mobile homes that are more than 14-1/3 feet wide..." as described in Section 10 of Senate Bill No. 142 from the regular session of 1991. Prior to Senate Bill No. 142, transporting of mobile homes wider than approximately 14 feet was not permitted in Michigan. Under Bill No. 142, mobile homes up to 16-feet in width are allowed by permit to operate for a period of one year. During this period of time, the current study was conducted to help evaluate how wider mobile homes in the state may affect traffic operations and how their increased width may affect their mobility on representative Michigan highways and intersections.

The study is focused on issues specifically related to *differential* effects that mobile home width (i.e., 16-ft widths versus 14-ft widths) may have on adjoining traffic and maneuverability. The study offers recommendations to state agencies regarding safe operation and allowed access to state highways for such vehicles. It should also be noted that in order to properly discriminate differences between 14-ft wide and 16-ft wide tractor/home combinations, a certain fundamental understanding of the basic behavior of this general class of vehicles is required and is accordingly pursued in various portions of the report.

The study relies on both *field data*, collected this past October and November on Michigan highways to evaluate driver behavior in the presence of mobile homes, and *computer analysis* to evaluate the low-speed maneuverability of mobile homes as well as their highway-speed dynamic characteristics. The field data were collected by observers following 13 different mobile homes using surveillance vehicles equipped with video cameras and time measurement equipment designed specifically for measuring certain motion characteristics of the mobile home and adjoining traffic. Results from that work appear primarily in Section 3 of Volume 2. The first portion of Section 3 (Vol. 2) reports on direct in-field measurements by observers (and previously contained in this study's

Interim Report in January). Further analysis of the videotape logs from the same field work are reported in the second portion of Section 3 (Vol. 2) and supplement those findings reported previously.

In Section 4 (Vol. 2), computer analyses are used to examine the low-speed turning and mobility of tractor/home combinations at intersections and freeway exit ramps. Highway speed analyses of how tractor/home combinations are affected by crosswinds and highway cross-slopes are addressed in Section 5 (Vol. 2). Similar analyses related to braking performance issues and weight distribution influences on tractor/home directional stability are examined in Section 6 (Vol. 2). Finally, conclusions and recommendations from the total project work appear in Section 7 (Vol. 2) as well as in Section 2 of this Volume.

Two previous studies [1, 2] conducted twenty years ago by the Michigan Department of State Highways for 12-ft wide and 14-ft wide tractor/home combinations are also noted because of their focus on similar issues. These two studies provide useful background for this discussion and the present concerns of transporting even wider home units on Michigan highways.

The authors would like to thank and acknowledge all the members of the steering committee who provided helpful guidance, suggestions, and technical assistance throughout the course of this study. The committee chairman, Mr. Richard Kuzma of MDOT, was especially helpful and acted as the primary liaison person with the research team at UMTRI. Mr. John Kanillopoolos from MDOT provided many useful suggestions and technical assistance related to highway design and geometrics. Thanks also to the Michigan State Police representatives, Insp. Bill Mohr and Sgt. Eric Johnson, and to their colleagues at the Coldwater and Grass Lake Weigh Stations for conducting axle load measurements on 26 tractor/home combinations. The Michigan Manufactured Housing representative, Mr. Tim DeWitt, likewise provided much appreciated assistance in obtaining basic design information on the home units examined in the study. Thanks also to Mr. Steve Zamiara of the Michigan Department of Commerce and to Mr. Dave Morena of the Federal Highway Administration for their helpful comments and suggestions. Lastly, the assistance of John Koch and Mike Campbell of UMTRI is acknowledged for their help in instrumenting the surveillance vehicles and collecting field data.

The funding for this study was provided by the Michigan Department of Transportation, the Federal Highway Administration, and the Michigan Department of Commerce.

2.0 Conclusions and Recommendations

—•— *Conclusions* —•—

The conclusions seen here summarize the basic findings described in Sections 2 through 6 of Volume 2. (Those conclusions for which home width per se plays a significant role are explicitly noted. Those conclusions that do not identify home width explicitly as a factor may be applied to homes of all widths, i.e., 14-ft, 16-ft, and 18-ft wide units.) Recommendations appear in the section immediately following the conclusions.

The results obtained from the field study observation data indicate that:

- During passing events on multilane divided highways, 16-foot wide tractor/home units encroached into the passing lane more than 14-foot wide units on average. Specifically, 16-foot wide units were observed encroaching an average 40.3% of the time for each passing event, while 14-foot wide units were observed encroaching an average of only 20.5 % of the time for each passing event.

- On multilane divided highways no significant relationship was found between the shoulder encroachment behavior of passing vehicles and the width of the tractor/home unit being passed.

- Passing vehicles (on multilane divided highways) were found to encroach onto the shoulder nearly two-thirds of the time regardless of the width of the tractor/home unit being passed.

- On two-lane, undivided roadways, drivers approaching an oncoming 16-foot wide tractor/home unit were more likely to use the shoulder than were drivers approaching 14-foot wide units. Approximately 57% of oncoming drivers used the shoulder when approaching a 16-foot wide unit; only 32% of drivers used the shoulder when approaching an oncoming 14-foot wide unit.

- The collected data also show that tractor/home units of both widths regularly travel in excess of the maximum speed specified on their travel permits. The 16-foot wide units were found to be travelling at almost the same average speeds as the 14-foot wide units.

- The field data collected under this study were focused almost exclusively on home shipments that entered the state from manufacturers and were travelling to dealer sites. No data were collected for home shipments that originated at in-state dealers and travelled to the final site locations of the homes. Consequently, the data reported here do reflect the more idealized travel portion of home shipments in the state that make use of higher quality freeways and roads. Even under these more ideal travel conditions, the data collected under this study still display a significant amount of time and miles spent on two-lane undivided highways. It should likewise be noted that the second portion of most deliveries (dealer to site) rely to an even greater extent on two-lane undivided secondary highways and county roads.

Videotape analyses from the field study completed since the Interim Report indicate that:

- 16-foot wide homes encroach into the left adjacent lane more often than do 14-foot homes.

- 16-foot homes use the right shoulder a greater proportion of the time than do 14-foot homes.

- Homes of both widths are more likely to encroach into the left adjoining lane when travelling on roadways with 11-foot lanes than on roadways with 12-foot lanes.

- Encroachment into the left adjacent lane is related to the condition of the right shoulder such that the poorer the condition of the right shoulder, the more time homes spend encroaching in the left adjacent lane.

- Homes of both widths spend less time using the right shoulder when that shoulder is in poor condition. This is the probable reason greater left adjacent lane encroachments were observed for roadways with right shoulders in poor condition.

- Homes of both widths are more likely to spend time encroaching into the left adjacent lane on two-lane roadways than multilane divided highways.

- Both cars and trucks are more likely to use the shoulder when passing 16-foot wide homes than when passing 14-foot wides, and trucks are even more likely to use the shoulder when passing than are cars.

- Cars are more likely to use the shoulder when passing homes on roadways with 11-foot lanes than on those with 12-foot wide lanes. In general, vehicles were more likely to use the shoulder when passing 16-foot wide homes than 14-foot wide homes independent of lane width. Insufficient data exist to determine if the use of shoulders for trucks follows the same pattern.

- Shoulder use of cars passing homes increases as the shoulder conditions improve. In general, vehicles were more likely to use the shoulder when passing 16-foot wide homes than 14-foot wide homes for all shoulder conditions. Insufficient data exist to determine if the use of shoulders for trucks follows the same pattern.

- Both cars and trucks were more likely to travel on the shoulder when approaching homes on two-lane undivided roadways (in the oncoming direction) than when passing on multilane divided highways (travelling in the same direction). Trucks were more likely than cars to use the shoulder when passing on both road types. In general, vehicles were more likely to use the shoulder when passing 16-foot wide homes than 14-foot wide homes when travelling on either multilane divided or two-lane undivided roadways.

- The results indicating increased shoulder use by vehicles passing tractor/home combinations suggest that the safety of these passing vehicles is likely degraded. This safety degradation is based on the fact that passing vehicles are more likely to use the shoulders, thus reducing the margin of error available to the passing vehicles. In addition, shoulder surface conditions are generally poorer than surface conditions of the normal travel lanes and can lead to increased control difficulty for the passing vehicles.

- It may sometimes be argued that because there is a lack of accident data demonstrating a clear relationship between manufactured home transport and accident experience that there is no safety degradation resulting from the movement of homes. This is not necessarily true if accidents, or near-accidents, involving vehicles in the vicinity of home units do occur and are indirectly influenced by their presence (e.g., traffic congestion, visibility restrictions, etc.). Degradation in safety margins can still occur even if it does not lead to specific, measurable, and well defined crash events that are ultimately recorded in the accident record.

The low-speed turning analyses described in Volume 2 indicate that:

- Both 14-ft, 16-ft wide, and 18-ft wide tractor/home units require considerably greater turning width at intersections (an additional 9 feet or more) than many other highway vehicles —including several types of large combination vehicles (doubles and triples).

14-ft wide by 80-ft long home units require approximately 35 feet of swept path width in turning through a normal right-hand intersection; 16-ft wide homes require 37 feet; and 18-ft wide units about 39 feet .

- Mobile home *width* is nearly as important a factor as *length* in contributing to the amount of space required by such vehicles when turning at intersections. Approximately half of the required turning space is due to the length of such vehicles; the other half of required turning space is attributable to their width.

- Curb clearance levels at turning intersections are diminished by approximately three feet when the home width is increased from 14-ft to 16-ft, and diminished by approximately six feet when the home width is increased from 14-ft to 18-ft.

- Minimum curb radii need to be increased approximately 7 feet for every 2 feet of additional home width in order to provide a comparable level of curb clearance.

- The more restrictive intersections likely encountered by tractor/home combinations in Michigan need to be at least 47 feet in radius for 14-ft wide homes, 53 feet in radius for 16-ft wide homes, and 60 feet in radius for 18-ft wide homes. These curb radii provide 1) minimal curb clearances while conducting 90-degree right-hand turns, and 2) avoid undesirable initial offsets by homes into oncoming traffic. (Curb radii less than these levels require tractor/home combinations to encroach, prior to the start of the turn, into oncoming traffic lanes in order to complete the turn with no curb-side conflicts.)

- Overhang or swing-out behavior exhibited by the outside rear-end of mobile homes during tight turning, as occurs at intersections, is particularly large (2 feet or more) when compared with overhang of conventional highway vehicles. A 16-foot wide home would increase this swing-out encroachment motion by an additional 1-foot margin beyond that seen for a 14-foot wide home; an 18-ft wide would increase this encroachment motion by an additional 2 feet over 14-ft wide homes.

- Encroachments into oncoming (or opposing) traffic lanes is the primary means available to tractor/home combination drivers for performing turns at more restrictive intersections (those existing intersections with smaller than required curb radii and not originally designed to accommodate vehicles of this size). The amount of required encroachment increases significantly with home width.

- A tractor/home unit that is just barely able to turn through a given intersection with minimal clearance, will require an additional 4 feet of offset (towards or into oncoming traffic lanes) in order to also turn through the same intersection with minimal clearance if its width is increased by 2 feet. This magnification, or doubling, of required space deriving from increased home width is significant, since all of the additional space required by the tractor/home combination (4 feet in this case) is obtained by offsetting the tractor/home combination towards oncoming traffic lanes. (A comparable 18-ft wide home would require an initial offset of 8 feet toward oncoming traffic lanes.)

- Most freeway exit ramps under low speed turning conditions do not provide special clearance problems for 14-ft wide and 16-ft wide tractor/home combinations. However, 18-ft wide homes will require the tractor driver to steer along an outer (larger radii) path on many ramps in order to provide additional clearance along the inner shoulder for the home. (On a 300-ft radius turning ramp, with the tractor centered in the turning lane, the wheel sets under an 80-ft long home unit will offtrack towards the inside of the curve approximately 6 feet at speeds less than 8 mph.)

The computer analyses of highway-speed conditions presented in Volume 2 indicate that:

- For tractor/home combinations operating at speeds of 45 mph under idealized (steady and non-varying) crosswinds of 25 mph, the rear-end of 80-ft long home units will offtrack laterally about 1 foot. These results are largely independent of width, though wider (and thereby heavier) home units do exhibit approximately 5% less offtracking (0.5 inches) per 2 feet of additional home width under these conditions.

- The same analyses indicate that when realistic crosswind profiles that include natural, random-like variations are accounted for as well, the level of peak lateral offtracking exhibited by the same set of tractor/home combinations increases from 1 foot to approximately 1.5 feet.

- Increasing vehicle speed from 45 mph to 55 mph (22%) increases the crosswind offtracking amount by an additional 13%.

- Home units that are 20% lighter than the average home unit examined here, will also show increases of 20% in crosswind offtracking levels.

- The random-like and variable component of natural crosswinds is an important characteristic that acts as an on-going excitation of the tractor/home combination system and that acts to amplify lateral space demands (versus more idealized, non-varying crosswind disturbances).

- The influence of most highway cross-slopes on offtracking of tractor/home combinations while travelling in a straight-line direction is small and largely independent of width. A highway having a 2% cross-slope induces about 0.22 feet of offtracking at the end of an 80-ft long home unit.

- Superelevated highway curves (freeway connectors with operating speeds of 45-55 mph), require less than a foot of additional lateral space to accommodate tractor/home combination offtracking tendencies along such curves. (Along a 1270-ft radius curve with 6.7% superelevation, the wheel sets under an 80-ft long home unit will offtrack towards the inside of the curve nearly 1 foot at a speed of 45 mph, and approximately 0.5 feet at a speed of 55 mph.)

The braking performance and hitch load analyses seen in Volume 2 indicate that:

- The braking capabilities of most tractor/home combinations are dependent primarily upon the towing tractor for stopping power. Since the tractor unit constitutes only 35% or so of the total combination vehicle weight, the braking ability of such vehicles is notably poor. Consequently, a strong disparity exists between the stopping capability of tractor/home combinations and most other highway vehicles.

- From speeds of 45 mph on dry high-friction pavements, approximately 200 feet of stopping distance is required for tractor/home combinations. Passenger cars typically require half this stopping distance from the same speed. Heavy trucks require about two-thirds this distance.

- From speeds of 55 mph on dry pavement, more than 300 feet of stopping distance is required for tractor/home combinations. Again, passenger cars typically require less than half this stopping distance and heavy trucks about two-thirds this distance.

- Slightly longer stopping distances are required for wider homes because of their increased weight.

- Over-braking by the tractor driver (inadvertent or emergency-induced) will typically result in an unstable jackknife response. This undesirable tendency further reduces the margin for error and controllability for the tractor driver during braking conditions.

- Tractor/home oscillatory behavior (or sway) at highway speeds is very sensitive to the hitch load percentage (percentage of home weight carried by the tractor at the hitch location). A normal or design value of 24% provides good damping and prevents unwanted oscillatory behavior. Reducing the hitch load percentage to a level of 12% can produce unstable oscillatory responses. Hitch load percentages in the vicinity of 18% produce moderate amounts of oscillatory behavior.

- Increasing vehicle speeds from 45 mph to 55 mph results in less system damping and increases the likelihood of oscillatory behavior, particularly when hitch load percentages fall below 20%.

- Wider and longer home units exhibit slightly less damping (or slightly greater oscillatory behavior) than shorter and narrower home units for the same speed conditions and hitch load percentages.

- Housing manufacturer design guidelines (described in Volume 2) are reasonable rules to follow in providing for adequate hitch load percentages and the number of axles on home units. The "2/3 rule" regarding axle locations results in a 24% hitch load percentage, provided the home unit has its weight uniformly distributed along its length.

— • — *Recommendations* — • —

The following recommendations, in general, identify tractor/home combinations operating along two-lane undivided highways as the primary focus of concern. The concern is especially magnified along such routes that have narrow and/or deteriorating shoulders, particularly for oversize homes wider than 14 feet. This scenario frequently results in tractor/home units encroaching across undivided highway centerlines into oncoming traffic lanes. This is not normally viewed as a reasonable method of ordinary transport practice for highway vehicles. Consequently, current transport of 16-ft wide homes along two-lane highways with particularly narrow shoulder widths is not supported by this study until shoulder width upgrades along these highway sections are undertaken. An interim/transitional period of operation for 16-ft wide homes is suggested as a possible temporary solution for permitting 16-ft wide transports to continue to operate during any shoulder reconstruction period. The study does not support a status quo position that permits continued indefinite access by oversize 16-ft wide homes to those two-lane undivided highways having limited width capacities.

In general, divided multilane freeway operations in rural, low traffic density areas with wide shoulders do not present a significant problem for transporting 14-ft or 16-ft wide homes. However, these same vehicles must ultimately access narrower secondary roadways. In doing so, their mobility is restricted and their presence reduces the normally accepted vehicle-to-vehicle spacing expected by other highway users. Accordingly, the aforementioned concerns regarding tractor/home combinations operating along two-lane undivided highways will still frequently apply in many cases.

The specific recommendations based upon the findings and observations of this study are that:

Highway Shoulder Upgrades

- If the State determines that it is in its interest to allow the movement of 16-ft wide homes over the highway, paved shoulder widths along two-lane undivided highways likely to be used by tractor/home combinations in Michigan, and not currently meeting recommended minimum widths (indicated below), should be upgraded to those recommended widths. In addition, gravel areas adjoining those paved shoulders should meet comparable width requirements to provide sufficient clearance for lateral overhang of the home. This recommendation is based upon consideration of cumulative lateral space requirements that account for home width, crosswind influences, highway cross-slope effects, driver steering uncertainties, and minimal buffer zones of 1 foot along both sides of the home unit, such that home encroachments across highway centerlines and into oncoming traffic lanes are avoided.

— For home widths of 14 feet, the minimum cleared width (consisting of the travel lane, the paved shoulder width, and the adjoining gravel width) should be at least 18 feet of which the total paved surface portion (travel lane and paved shoulder area) is at least 16 feet.

— For home widths of 16 feet, the minimum cleared width should be at least 20 feet of which the total paved surface portion (travel lane and paved shoulder area) is at least 17 feet.

— For home widths of 18 feet, the minimum cleared width should be at least 22 feet of which the total paved surface portion (travel lane and paved shoulder area) is at least 18 feet. (If the wheel track for 18-ft wide homes exceeds 9' 6", an additional 1 foot of shoulder pavement is recommended.)

These recommended minimum paved surface widths (lane + shoulder) suggest that for two-lane highways with lane widths of 12 feet, the paved shoulder should be at least 4 feet wide to accommodate 14-ft wide homes, 5 feet wide to accommodate 16-ft wide homes, and 6 feet wide to accommodate 18-ft wide homes. (Eleven-foot wide travel lanes would increase these recommended paved shoulder widths by 1 foot.)

[These recommendations are based upon a simple formula for estimating the minimum cleared width (i.e., travel lane, paved shoulder, and additional gravel width) given by, $C = W + 4.25$, where W is the width of the home unit and C is the minimum cleared width. The 4.25 (feet) value is used to account for the combined effects of crosswind influences (1.5 feet), highway cross-slopes (0.25 feet), normal driver steering uncertainty (at least 0.5 feet), and 1 foot buffer margins along both sides of the home unit (2 feet).]

- The recommended upgrades do affect shoulder design and strength issues. Such upgrades would need to strengthen affected shoulder areas (by increasing pavement depths) in order to handle the increased loads regularly being carried along such routes.

- For those two-lane highway segments requiring shoulder widening, a transitional time period will exist prior to completion of the recommended shoulder widening construction. During this transitional period, an additional lead escort vehicle (preferably from a police agency) should be provided at these specific route sections to slow down and warn oncoming traffic of likely encroachments across the centerline by the home unit.

- Use of an additional lead escort vehicle (police or otherwise), itself, in lieu of the accompanying shoulder widening effort recommended above, is not suggested as an alternate long term solution along such routes, particularly for homes wider than 14 feet. Such escort activities by police agencies are only being identified as one possible method for improving the safety along such routes under a well defined short-term arrangement.

Highway Intersections

- Curb radii at intersection turns along routes of tractor/home combinations should generally be increased to at least 60 feet to provide sufficient curb clearance and avoidance of encroachments by home units into oncoming traffic lanes at the start of intersection turning maneuvers. Design values for specific intersection geometries could be based upon the information contained in Volume 2.

- Traffic control and stoppage is recommended for those restricted intersections that require encroachments by home units into oncoming traffic lanes from their initial turning position. Cross-road traffic will always be stopped and cleared in any event to allow the tractor/home to complete its turn into the lanes of oncoming cross traffic. However, additional assistance is likely required at many restricted intersections in order to not only control the cross-road traffic, but to stop and control the following and opposing traffic as well at the start of intersection turns. Traffic control under these circumstances should be exercised by an agency having the proper authority.

Tractor/Home Braking Performance

- Addition of brakes to all axles (as opposed to one or two) on the home unit is strongly recommended to improve the braking performance of most tractor/home combinations. This will also help to alleviate the braking demand upon the tractor unit and help to better stabilize the combination vehicle during emergency stops. Jackknifing tendencies will likewise be reduced. This raises the question of how to best accomplish this because of existing federal regulations and/or interstate commerce issues.

- Because of the limited stopping capability of existing tractor/home combinations and their tendency to jackknife under emergency braking, sufficient space should be provided between the lead escort vehicle and the towing tractor. This lead buffer zone should be maintained free of traffic with highly visible signing located on the back of the lead escort vehicle and the front of the tractor to warn adjacent vehicles out of this zone. For freeway travel at speeds of 45 mph, the length of this buffer zone should be at least 250 feet. At lower speeds of 25 mph, the buffer zone should be maintained clear of traffic for a distance of 150 feet. (These recommended clearance distances reflect a perception and reaction time of 2.5 seconds for the tractor driver and the stopping ability of tractor/home combinations relative to passenger cars.)

- The lead escort vehicle, in cooperation with the tractor driver, should maintain reasonable lead distances ahead of the tractor/home combination so as to discourage other traffic from wandering into the lead buffer zone. Lead distances should not exceed 500 feet on the freeway and 200 feet along slower 25 mph routes having additional traffic.

- Slippery surface conditions further aggravate the braking capabilities of tractor/home combinations and travel should not be allowed during snow/ice conditions.

Speed Limits and Enforcement

- Because of the limited stopping ability of tractor/home combinations, maximum speeds for such vehicles should be limited to 45 mph on freeways. (At freeway speeds of 55 mph, the recommended buffer zone would have to grow to a distance of nearly 400 feet and could not be easily maintained free of other traffic by the lead escort vehicle.) On two-lane undivided highways, where sight distances are limited and travel conditions are less ideal, the current speed limit of 35 mph should be maintained.

- Enhanced enforcement of speed limits for tractor/home combinations is recommended. Field observations of average tractor/home combination travel speeds in this study indicated routine violation of allowed limits on their permits. Based upon the braking performance disparities that exist between tractor/home combinations and other highway vehicles, more vigorous enforcement of speeding is recommended. Computer-based analyses also indicate that greater oscillatory behavior and considerably greater stopping distances are exhibited by these vehicles as speeds increase. Responsibility for safe operation of the units rests largely on the tractor operators and their employers. Speed regulation possibilities to consider by companies or individuals responsible for shipping these homes could include: A) installing automated data recorders on all tractors used to ship homes with the data from these recorders being sent to MDOT to ensure compliance, or B) providing an equivalent method to guarantee compliance. MDOT should be empowered to withhold shipping permits from those companies or individuals that have an excessive record of speed limit violation.

Tractor/Home Transport Practice

- Design practice for home units that result in approximately a 24% hitch load percentage is supported. The axle placement rule noted in Volume 2 that locates the axle-set centerline two-thirds behind the front of the home is an example. In all cases, hitch load percentages should be maintained in the 20% to 30% range. Side-to-side (sway) oscillations begin to develop in tractor/home combinations when hitch load percentages fall below the 20% level, thereby requiring additional lateral space and increasing the chances of lateral encroachments.

- The 6000 lb per axle (maximum) rule for determining the number of axles to use on home units, also described in Volume 2, is likewise supported and recommended.

Existing Permit Practice

- Existing permit rules regarding time of day restrictions, urban area restrictions, escort practices, seasonal restrictions, and designated routing by knowledgeable state authorities is supported.

- A uniform height limitation on home units (e.g., 13' 6" , or, some equivalent) number should be determined based upon a survey of bridge height clearances and similar limitations along the routes designated for all tractor/home combinations.

Bridge Crossings

- Traffic control and stoppage is recommended at bridge crossings having widths less than 30 feet for 14-ft wide homes, 34 feet for 16-ft wide homes, and 38 feet for 18-ft wide homes.

Escort Vehicles and Driver Training

- Given the longer stopping distances required by tractor/home units, it is important that escort vehicles work in close cooperation with the tractor/home units to control traffic travelling in close proximity to the homes. The role escort vehicles play in traffic control is critical such that specific, detailed, and approved training programs should be developed and enforced for any and all drivers of tractor/home escorts. Of critical importance in this training is the need to ensure that a clear lane of movement is available to the tractor/home unit for any lane change or other maneuvers that involve the tractor/home unit changing direction or speed. It is also important that escort vehicle drivers be advised of the dangers associated with both leading the tractor/home unit too closely or allowing other vehicles to get between the front of the tractor/home unit and the lead escort. The tractor/home unit requires longer distances to stop and complete other maneuvers, and it is the role of the escorts to assure that proper distances are maintained between the tractor/home unit and other vehicles. Escort training programs may be able to be "piggy-backed" onto existing specialized driving courses. Such piggy-backing would reduce costs of training and may in fact enhance more general knowledge and skills of escort team drivers to maximize their ability to escort manufactured housing units. To ensure escort drivers do complete authorized courses, it is recommended that escort drivers be certified through some official process and that only certified drivers be permitted to escort home units.

  It is probably true that proper escort vehicle behavior may frustrate the inexperienced and generally uninformed public, especially because proper escort behavior may involve impeding the planned passing behavior of other vehicles. However, this frustration may be mitigated by a thorough public information and education program to inform the general driving public about the dangers associated with improper passing, following, and lead distances when driving around the tractor/home units.

Public Information & Education Programs

- Because the general driving public is likely unaware of the maneuvering limitations of tractor/home units and the importance of maintaining a safe following, leading, and passing distance when travelling near these vehicles, a comprehensive PI&E effort is recommended. This PI&E effort should be concentrated during the beginning of peak delivery periods, but should continue throughout periods when tractor/home units are travelling on the roadways.

- A comprehensive PI&E strategy involving all media (print and broadcast) should be employed to reach the broadest possible audience in those areas most affected by home shipments. This may include special educational posters at rest areas, developing informational articles for newspapers to print periodically, developing public service announcements for radio and television, and other forms of media. These PI&E materials should stress that it is as important, if not more so, for the general driving public to drive carefully and cautiously around tractor/home units than for the tractor/home unit drivers. A special emphasis of the PI&E campaign should be to instruct drivers not to try to "beat" the escort vehicles. The escorts are there to protect the area around the tractor/home unit to ensure safe transportation for both the home and those driving in the proximity of the home. This special emphasis should also stress the importance of not getting between the escort vehicles and the tractor/home unit. This is especially true for vehicles that may want to duck between the tractor/home unit and the lead escort vehicle. This area (between the tractor/home unit and lead escort) is there as a buffer zone providing the tractor/home unit additional space in which to complete stops safely.

Urban Freeways and Multilane Undivided Highways

- Although this study did not gather much data along urban freeways and multilane undivided highways, it was apparent that under such congested traffic conditions, tractor/home combinations introduce more complicated traffic situations and potential for conflicts. Accordingly, the study recommends continued support of existing geographical and time-of-day restrictions on tractor/home combinations along urban freeways and multilane highways.

- Along more rural multilane undivided highways, shoulder quality and width seemed to vary to a much greater extent than on interstate freeways. Under these travel conditions, encroachments by the home into the passing lane are likely to be more frequent. Consequently, greater vigilance and control of surrounding traffic by the escort vehicles should be emphasized under these circumstances.

References

1. 12-Foot Wide Mobile and Modular Home Transit Study on the State Trunkline System, TSD-RD-206-72, Standards and Development Unit, R & D Section, Traffic and Safety Division, Michigan Department of State Highways, 1972.

2. 14-Foot Wide Mobile and Modular Home Transit Study, TSD-G-188-71, Standards Unit, Geometrics Section, Traffic and Safety Division, Michigan Department of State Highways, 1971.

Related Bibliography

Zeeger, C.V. et al, "Safety of Wide Trucks on Narrow Roadways," Contract No. DTFH61-87-Z-00077, Final Report, 1990.

Decabooter, P.H. and Solberg, P.E., "Operational Considerations Relating to Long Trucks in Urban Areas," Paper No. 880071, 68th Annual Meeting, TRB, 1989.

"A Policy on Geometric Design of Highways and Streets - 1990", Washington D.C., AASHTO, 1990.

Final Report to the Michigan State Legislature and Steering Committee

regarding the

16-ft Wide Mobile Home Study

Report No. UMTRI-92-18-2
(Volume 2)

C. MacAdam
F. Streff
C. Christoff
S. Karamihas

May 15, 1992

UMTRI The University of Michigan
Transportation Research Institute

Final Report to the Michigan State Legislature and Steering Committee

regarding the

16-ft Wide Mobile Home Study

Prepared in Cooperation with
The U.S. Department of Transportation
Federal Highway Administration
and
Michigan Department of Transportation
By

The University of Michigan
Transportation Research Institute

Report No. UMTRI-92-18-2

(Volume 2)

C. MacAdam
F. Streff
C. Christoff
S. Karamihas

May 15, 1992

Amount Printed: 40 Total Cost: $285.98 Per Copy: $7.15

Technical Report Documentation Page

1. Report No. FHWA-MI-RD-92-03 UMTRI-92-18-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Final Report to the Michigan State Legislature and Steering Committee Regarding the 16-ft Wide Mobile Home Study (Volume 2)		5. Report Date May 15, 1992
		6. Performing Organization Code
7. Author(s) C. MacAdam, F. Streff, C. Christoff, and S. Karamihas		8. Performing Organization Report No. UMTRI-92-18-2
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road, Ann Arbor, Michigan 48109		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. MDOT 91-1291
12. Sponsoring Agency Name and Address Michigan Department of Transportation Lansing, Michigan		13. Type of Report and Period Covered Final 9/12/91 - 5/15/92
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This document represents the final reporting of findings from a study of 16-foot wide mobile homes by the University of Michigan Transportation Research Institute on behalf of its sponsors, the Michigan State Legislature and its intermediary steering committee comprised of representatives from the Michigan Department of Transportation, the Michigan Department of Commerce, the Michigan State Police, and the manufactured housing industry. A primary purpose of the study is to evaluate "the mobility, turning ability, and transporting of mobile homes that are more than 14-1/3 feet wide..." as described in Section 10 of Senate Bill No. 142 from the regular session of the 1991 Michigan State Legislature. The study is focused on issues specifically related to differential effects that mobile home width (i.e., 16-ft widths versus 14-ft widths) may have on adjoining traffic and maneuverability. Recommendations are offered regarding safe operation and allowed access to state highways for such vehicles.

The study relies on both *field data,* collected this past October and November on Michigan highways to evaluate driver behavior in the presence of mobile homes, and *computer analysis* to evaluate the low-speed maneuverability of mobile homes as well as their highway-speed dynamic characteristics.

17. Key Words mobile home, offtracking, encroachment, highway design, wide load, vehicle width, modular home, highway use, crosswind, maneuverability, traffic, mobility, braking, dynamics, stability, hitch, videotape, wind		18. Distribution Statement No restrictions	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 140	22. Price

Table of Contents

1.0 Introduction

This document represents the final reporting of findings from a study of 16-foot wide mobile homes by the University of Michigan Transportation Research Institute on behalf of its sponsors, the Michigan State Legislature and its intermediary steering committee comprised of representatives from the Michigan Department of Transportation, the Michigan Department of Commerce, the Michigan State Police, and the manufactured housing industry. A primary purpose of the study was to evaluate "the mobility, turning ability, and transporting of mobile homes that are more than 14-1/3 feet wide..." as described in Section 10 of Senate Bill No. 142 from the regular session of 1991. Prior to Senate Bill No. 142, transporting of mobile homes wider than approximately 14 feet was not permitted in Michigan. Under Bill No. 142, mobile homes up to 16-feet in width are allowed by permit to operate for a period of one year. During this period of time, the current study was conducted to help evaluate how wider mobile homes in the state may affect traffic operations and how their increased width may affect their mobility on representative Michigan highways and intersections.

The study is focused on issues specifically related to *differential* effects that mobile home width (i.e., 16-ft widths versus 14-ft widths) may have on adjoining traffic and maneuverability. The study offers recommendations to state agencies regarding safe operation and allowed access to state highways for such vehicles. It should also be noted that in order to properly discriminate differences between 14-ft wide and 16-ft wide tractor/home combinations, a certain fundamental understanding of the basic behavior of this general class of vehicles is required and is accordingly pursued in various portions of this report.

As will be described in the following sections, the study is relying on both *field data*, collected this past October and November on Michigan highways to evaluate driver behavior in the presence of mobile homes, and *computer analysis* to evaluate the low-speed maneuverability of mobile homes as well as their highway-speed dynamic characteristics. The field data were collected by observers following 13 different mobile homes using surveillance vehicles equipped with video cameras and time measurement equipment designed specifically for measuring certain motion characteristics of the mobile home and adjoining traffic. Results from that work appear primarily in Section 3. The first portion of Section 3 reports on direct in-field measurements by observers (and previously contained in this study's Interim Report in January). Further analysis of the videotape logs from the same field work are reported in the second portion of Section 3 and supplement those findings reported previously.

In Section 4, computer analyses are used to examine the low-speed turning and mobility of tractor/home combinations at intersections and freeway exit ramps. Highway speed analyses of how tractor/home combinations are affected by crosswinds and highway cross-slopes are addressed in Section 5. Similar analyses related to braking performance issues and weight distribution influences on tractor/home directional stability are examined in Section 6. Finally, conclusions and recommendations from the total project work appear in Section 7.

Two previous studies [1, 2] conducted twenty years ago by the Michigan Department of State Highways for 12-ft wide and 14-ft wide tractor/home combinations are also noted because of their focus on similar issues. These two studies provide useful background for this discussion and the present concerns of transporting even wider home units on Michigan highways.

The authors would like to thank and acknowledge all the members of the steering committee who provided helpful guidance, suggestions, and technical assistance throughout the course of this study. The committee chairman, Mr. Richard Kuzma of MDOT, was especially helpful and acted as the primary liaison person with the research team at UMTRI. Mr. John Kanillopoolos from MDOT provided many useful suggestions and technical assistance related to highway design and geometrics. Thanks also to the Michigan State Police representatives, Insp. Bill Mohr and Sgt. Eric Johnson, and to their colleagues at the Coldwater and Grass Lake Weigh Stations for conducting axle load measurements on 26 tractor/home combinations. The Michigan Manufactured Housing representative, Mr. Tim DeWitt, likewise provided much appreciated assistance in obtaining basic design information on the home units examined in the study. Thanks also to Mr. Steve Zamiara of the Michigan Department of Commerce and to Mr. Dave Morena of the Federal Highway Administration for their helpful comments and suggestions. Lastly, the assistance of John Koch and Mike Campbell of UMTRI is acknowledged for their help in instrumenting the surveillance vehicles and collecting field data.

The funding for this study was provided by the Michigan Department of Transportation, the Federal Highway Administration, and the Michigan Department of Commerce.

An accompanying Executive Summary volume also summarizes the main conclusions and recommendations contained within this report.

2.0 Description of Vehicle and Its Transport Along Highways

This section of the report provides a general description of the basic vehicle configuration under study. A set of axle weight-scale measurements conducted by the Michigan State Police on various tractor/home combinations at two locations in Michigan are also presented in this section of the report. These provide representative size and weight data on actual tractor/home combinations (in the 70- to 80-ft length category) typically seen operating in Michigan. Basic observations regarding the range of size and weight characteristics that are representative of most tractor/home configurations from this class of vehicles are then presented along with supplementary design information from the housing industry.

General Description of the Vehicle and Its Transport Along Highways

In Figure 2-1 the basic geometry of a 16-ft wide home unit and towing tractor is described. The overall length of the combination vehicle is 95 feet with the home unit length of 79 feet constituting the major element. In general, the homes observed in this study have normally been equipped with either 4 or 5 axle sets depending upon the weight of the home. However, certain 14-ft wide homes that may be lighter in weight are equipped with only 3 axles. Home weights normally range in the vicinity of 20 to 33 thousand pounds depending upon the particular size, construction material used, and the degree of interior finishing by the manufacturer prior to shipment. Typically the towing tractor has a 10-foot wheelbase and is equipped with a ball hitch (located 4 feet or so behind of the rear tractor drive axle) for hauling the home unit. A 3-ft tongue is usually used at the front of each home unit for connecting to the tractor ball hitch.

Transporting of 16-ft wide homes requires the kind of vehicle positioning on the highway as depicted in Figure 2-2. The tractor/home combination vehicle is required to use most of the shoulder area in order to maintain some clearance margin for adjoining traffic on the highway side of the home. In practice, this idealized view is difficult to maintain and some wandering of the combination vehicle does occur causing intermittent encroachments by the home unit outside of its designated 12-ft lane.

Figures 2-3 through 2-5 help to further illustrate how lane width and shoulder characteristics on freeways and two-lane highways affect the wheel placements of both 14-ft wide and 16-ft wide homes. The wheel/axle assemblies used in transporting all such homes provide a maximum spread of 9.5 feet as noted in these figures. Consequently, the shoulder-side wheels on the mobile home are required to track along different portions of the shoulder area — depending upon the lane width, shoulder width, and lateral positioning of the vehicle by the tractor driver. Along freeways that have wide 8-ft or 10-ft shoulders (Figure 2-3), ample room is generally available to 14-ft and 16-ft wide home units, except when disabled vehicles or miscellaneous debris may occupy the shoulder, thereby requiring the home units to move leftward into the passing lane.

Along two-lane undivided highways (as depicted in Figures 2-4 and 2-5), the situation is considerably more restrictive because of the limited paved shoulder widths normally available on many of these roadways. Deterioration of paved shoulders, disabled vehicles or debris, reduced maneuvering margins for normal driver steering behavior, and environmental disturbances will induce greater numbers of encroachments across the centerline and into oncoming traffic lanes on these types of highways.

Figure 2-1. Description of an Example Mobile Home and Towing Tractor Combination as Measured by MDOT.

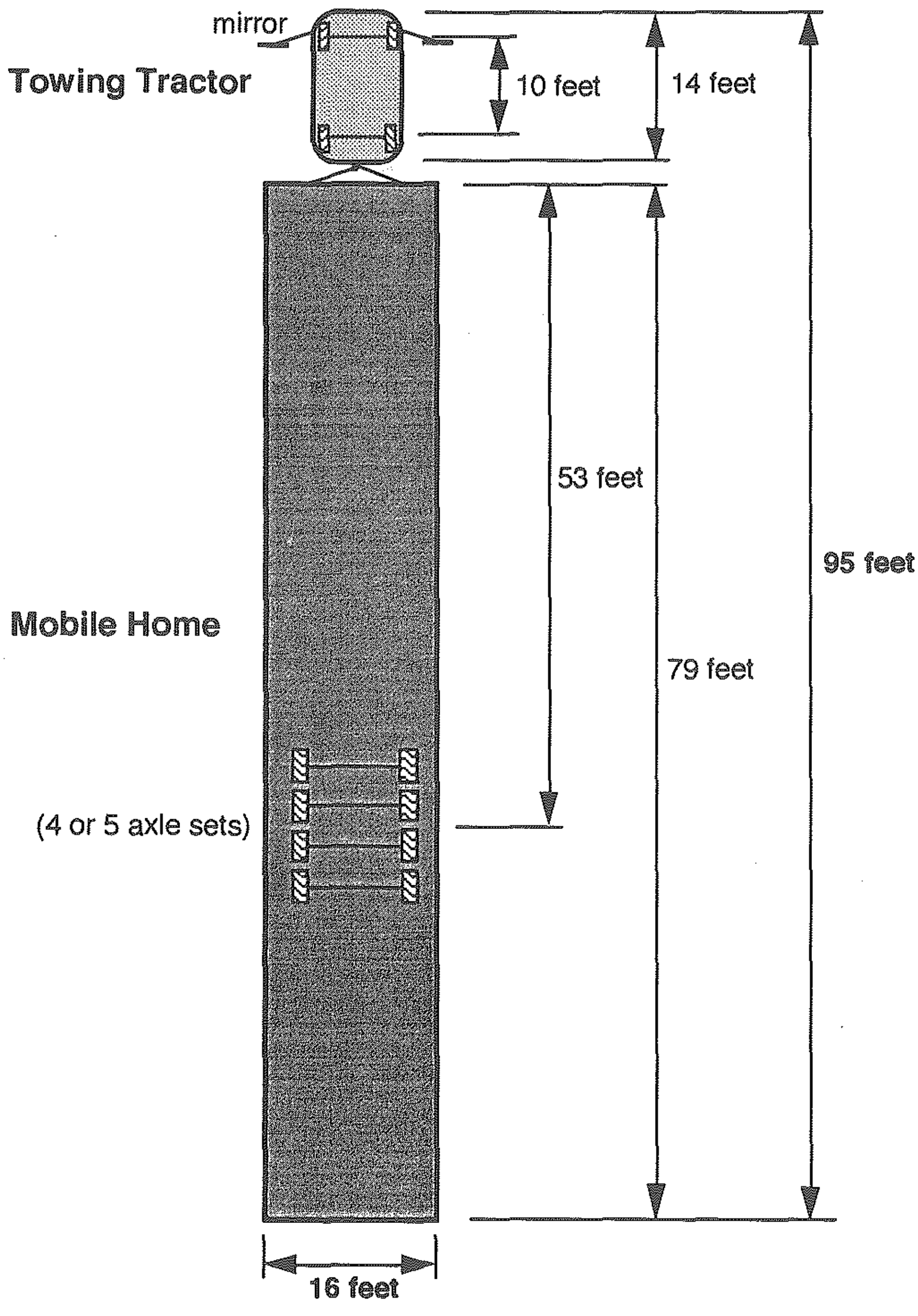


Figure 2-2. Freeway Transport of 16-ft-Wide Mobile Homes.

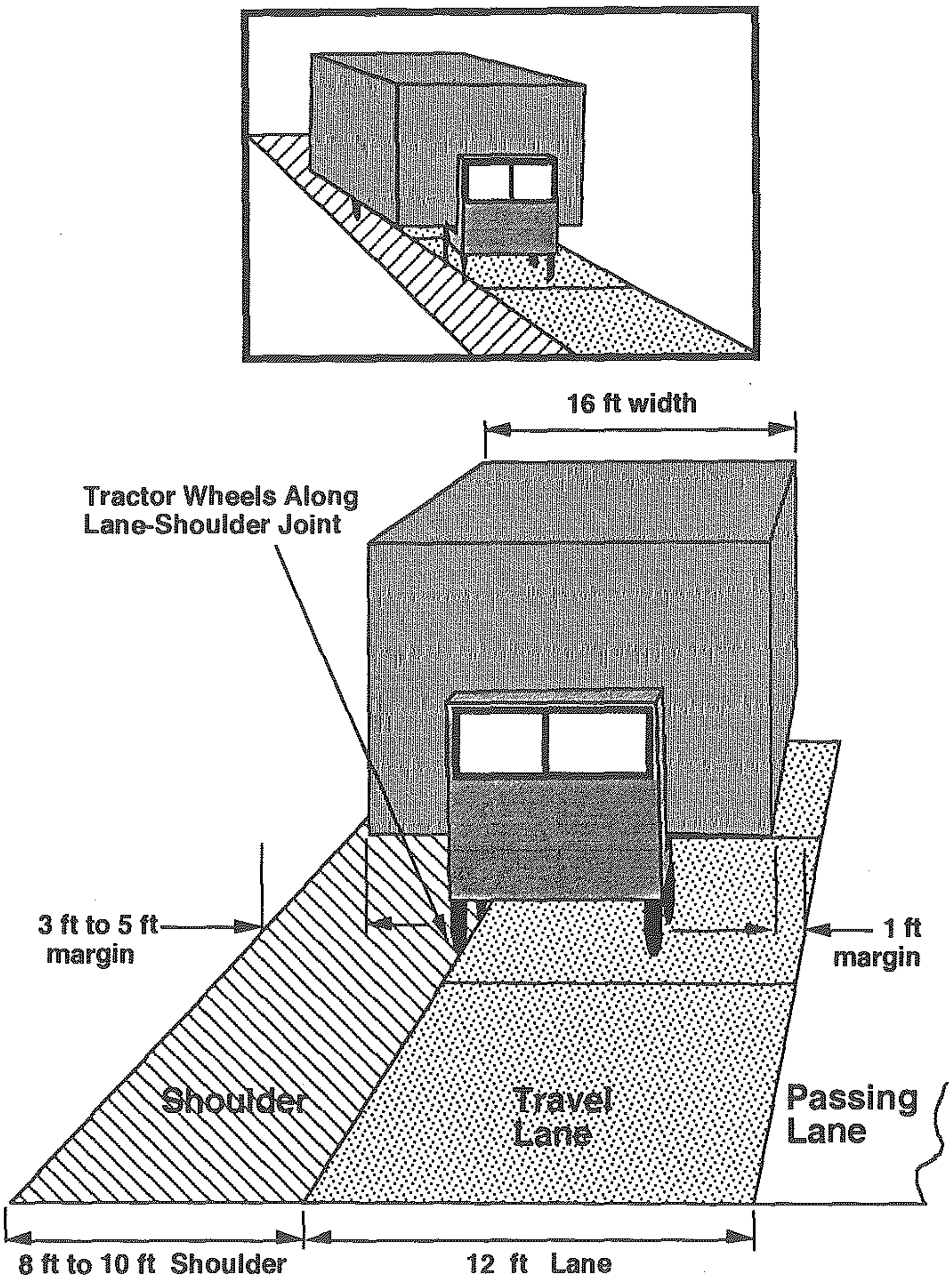


Figure 2-3. Wheel Placement on Freeway for 14-ft and 16-ft Wide Homes.

(View from Rear)

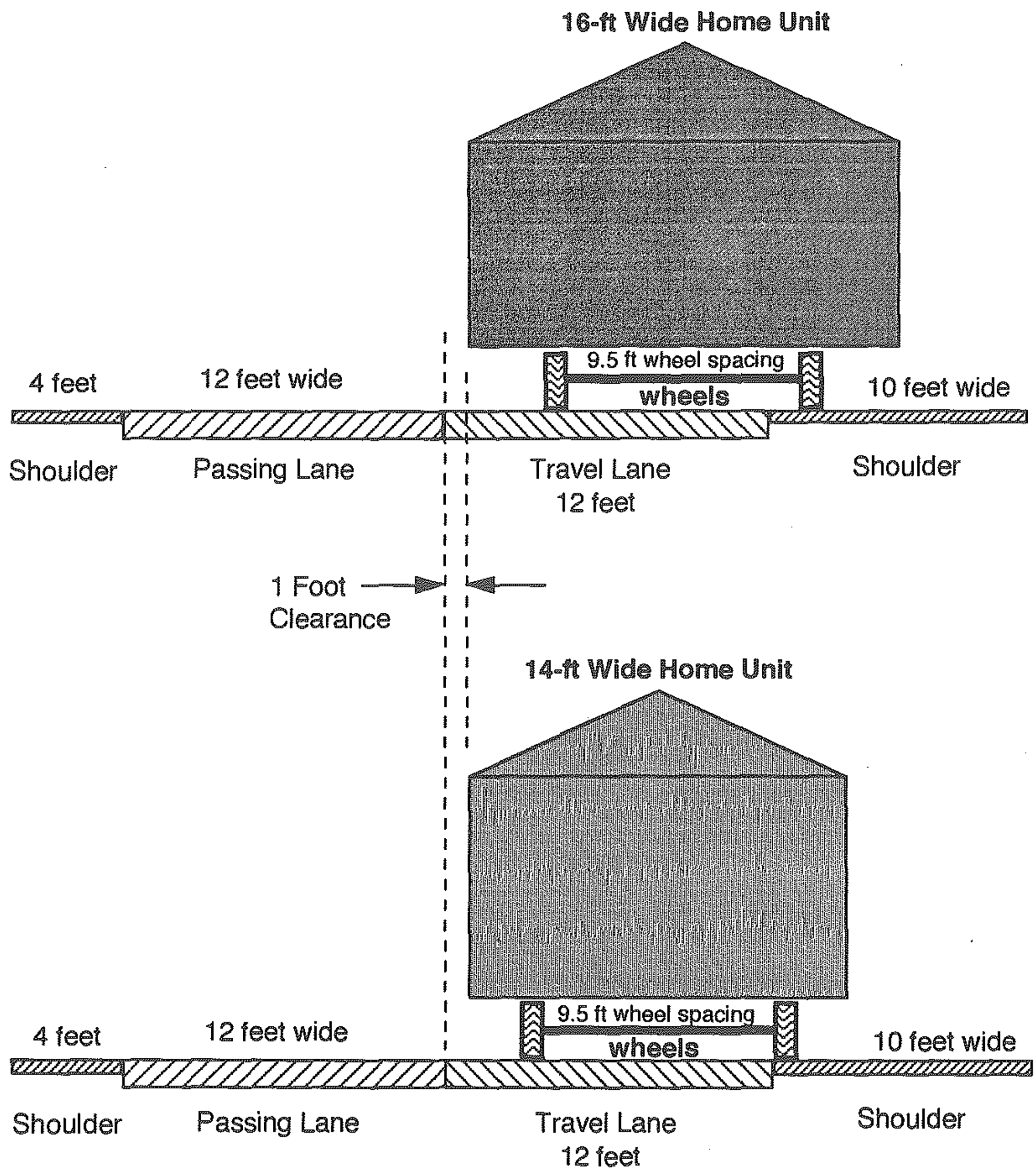


Figure 2-4. Wheel Placement on Two-Lane Highway for 14-ft and 16-ft Wide Homes

(View from Rear)

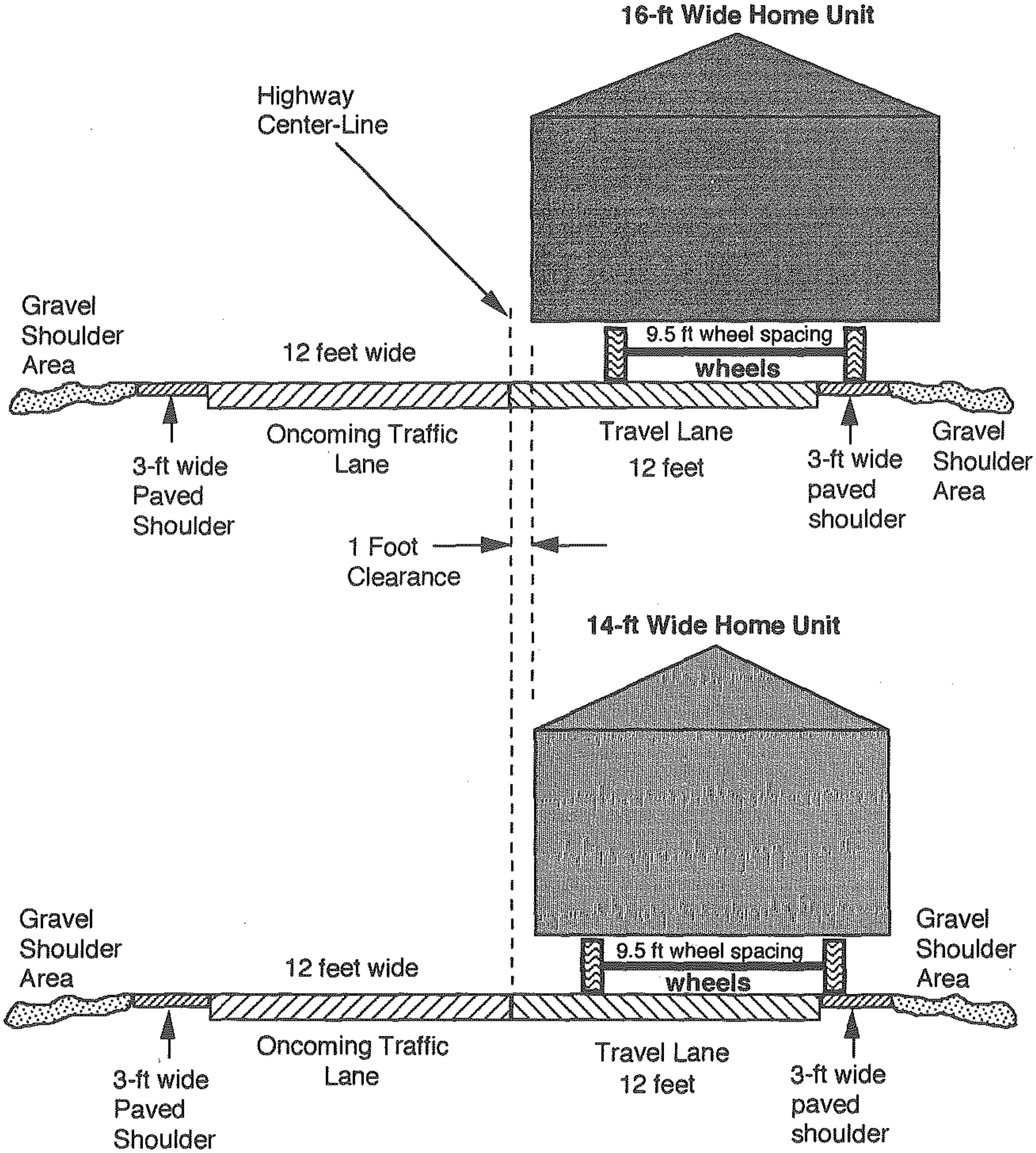
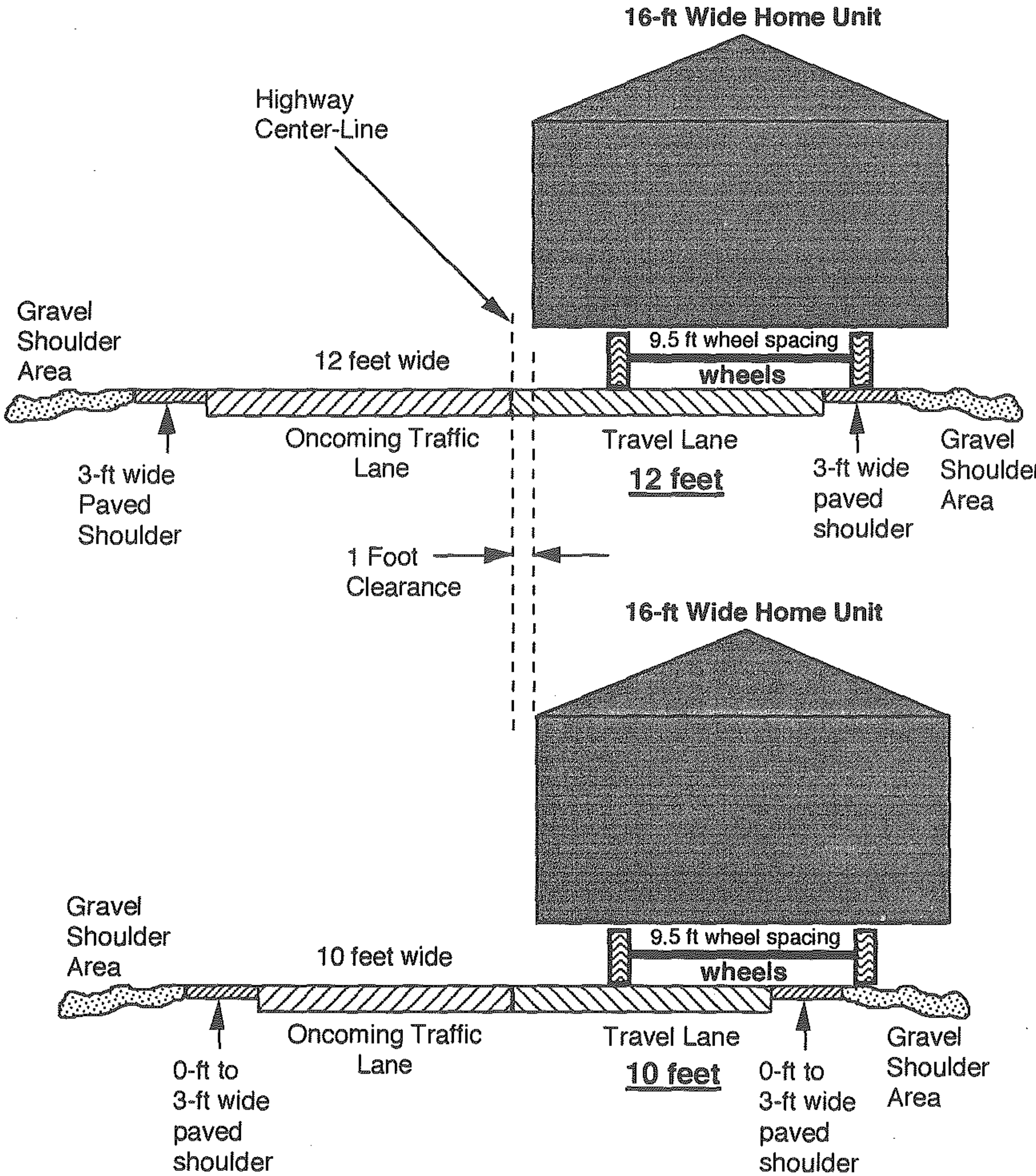


Figure 2-5. Influence of Lane Width on Wheel Placement on Shoulder for Two-Lane Highways

(View from Rear)



Axle Weight Measurements by the Michigan State Police

The Michigan State Police were asked during the study to weigh a number of tractor/home combinations in order to gather some representative data on actual axle weights, widths, and home lengths. This occurred over a time period of two to three weeks at two different weigh-scales in Michigan. The two scale facilities are located near Coldwater along I-69 N (just North of the Indiana-Michigan state line) and near Grass Lake along I-94 E (just east of Jackson).

Table 2-1 shows the measurements conducted at the Coldwater weigh-scale. Since a large percentage of manufactured homes (perhaps 50% or so) enter the state along this route, this particular facility was an ideal location for these measurements. Several columns appear in Table 1 and are defined from left to right as follows: Column 1 is the length of the home unit; column 2 is the width of the home unit; column 3 is the overall length (OAL) of the tractor/home combination. Columns 4-7 are the measured axle loads starting from the front of the vehicle at the tractor steer axle, then the tractor drive axle, and continuing rearward with the number of axles on the home unit (axles 3 —> last axle). Column 11 (GVW) is the gross vehicle weight, or, sum of all axle loads (tractor and home). Column 12 (Susp 1) is the tractor front suspension load (or axle 1 load). Susp-2 in column 13 is the tractor rear suspension load (or axle 2 load). Susp-3, appearing in the last column, is the total suspension load under the mobile home (or the sum of axles 3 —> last axle).

Six groupings of data appear in Table 2-1 and are simply the measurements of 15 different tractor/home combinations categorized by length, width, and the number of axles. For example, the first two rows of data correspond to 16-ft wide and 80-ft long homes that have 4 axles on the home unit. The next group of data are for the same size home but for homes having 5 axle sets (i.e., load data for Axle-3 through Axle-7). For all but the last category at the bottom of the table (where only one vehicle appears), a row labelled **Average** displays the average value of the axle weights appearing above each particular group.

Table 2-2 contains similar data for measurements performed at the Grass Lake facility. However, in this table certain data were not as readily measured on the tractor unit and "x's" appear instead in those table locations. (To avoid possible confusion stemming from the incomplete data, the **Average** rows are also deleted in this table.)

The primary difference between the measurements at the two weigh scale sites is the suspension load of the home unit (Susp-3) for the 70-ft x 16-ft home group (fourth category). The Grass Lake (Table 2-2) measurements appear to be about 15% or so higher than similar size homes measured at Coldwater. The reasons for this are unclear but may

Table 2-1. Axle Weight Measurements by the Michigan State Police at the Coldwater Weigh Station on I-69.

(15 Tractor/Home Combinations Grouped by Length, Width, and Number of Axles)

Length (ft)	Width (ft)	OAL (ft)	Axle-1 (LB)	Axle-2 (LB)	Axle-3 (LB)	Axle-4 (LB)	Axle-5 (LB)	Axle-6 (LB)	Axle-7 (LB)	GVW (LB)	Susp-1 (LB)	Susp-2 (LB)	Susp-3 (LB)
80	16	95	8100	16280	6770	6740	5710	3660		47260	8100	16280	22880
80	16	98	7930	15210	5340	6360	5010	4360		44210	7930	15210	21070
Average:		**96.5**	**8015**	**15745**	**6055**	**6550**	**5360**	**4010**		**45735**	**8015**	**15745**	**21975**
80	16	98	6940	14240	6930	3940	3390	5420	4740	45600	6940	14240	24420
77	16	95	6750	15290	6630	5060	4470	3290	2950	44440	6750	15290	22400
Average:		**96.5**	**6845**	**14765**	**6780**	**4500**	**3930**	**4355**	**3845**	**45020**	**6845**	**14765**	**23410**
80	14	95	7640	16520	6430	5830	6060	3510		45990	7640	16520	21830
80	14	98	7710	14320	4780	5080	4710	5350		41950	7710	14320	19920
Average:		**96.5**	**7675**	**15420**	**5605**	**5455**	**5385**	**4430**		**43970**	**7675**	**15420**	**20875**
72	16	90	6900	15370	6530	5920	5160	4560		44440	6900	15370	22170
72	16	95	7260	16920	5370	4070	6670	5540		45830	7260	16920	21650
70	16	90	7420	16910	5340	5110	5430	4520		44730	7420	16910	20400
70	16	85	7430	17340	5660	5870	6090	5930		48320	7430	17340	23550
70	16	90	8550	17680	3200	6920	5100	3880		45330	8550	17680	19100
70	16	88	8110	15830	6700	5110	4890	3530		44170	8110	15830	20230
Average:		**90**	**7612**	**16675**	**5467**	**5500**	**5557**	**4660**		**45470**	**7612**	**16675**	**21183**
70	14	90	7860	13700	6510	6700	4930			39700	7860	13700	18140
70	14	88	7500	14580	7550	4960	4460			39050	7500	14580	16970
Average:		**89**	**7680**	**14140**	**7030**	**5830**	**4695**			**39375**	**7680**	**14140**	**17555**
70	14	90	7280	13030	5240	4030	4790	4680		39050	7280	13030	18740

Table 2-2. Axle Weight Measurements by the Michigan State Police at the Grass Lake Weigh Station on I-94.

(11 Tractor/Home Combinations Grouped by Length, Width, and Number of Axles)

Length (ft)	Width (ft)	OAL (ft)	Axle-1 (LB)	Axle-2 (LB)	Axle-3 (LB)	Axle-4 (LB)	Axle-5 (LB)	Axle-6 (LB)	Axle-7 (LB)	GVW (LB)	Susp-1 (LB)	Susp-2 (LB)	Susp-3 (LB)
80	16	x	x	x	5960	6570	5960	6290					
80	16	x	8040	15620	7640	7140	4090	5140		47670	8040	15620	24010
80	16	x	x	x	5030	6810	4870	3860	5010				25580
80	14	95	x	x	5210	6450	6910	5300					23870
72	16	95	x	x	5600	4200	6680	7390					23870
70	16	x	x	x	5530	5570	5820	6300					23220
70	16	x	x	x	5680	5980	6600	6400					24660
74	16	x	7320	19040	6760	7820	5870	5400		52210	7320	19040	25850
70	14	x	x	x	7050	6780	5380						19210
70	14	x	7350	13520	6580	6200	5360			39010	7350	13520	18140
70	14	x	x	x	5560	5810	4410	3990					19770

(X 's denote missing or unmeasured data) be related to the manufacturing sources shipping homes along that route, or perhaps a greater percentage of homes being sold in the western Detroit area with additional interior finishings. Far greater numbers of measurements would be needed to identify any significant trends.

For purposes of estimating approximate tongue loads acting on the tractor hitch (i.e., from the weight of the home), a generic 16,500 lb tractor was assumed in a special set of weight distribution calculations. Using the axle load data available from Table 2-1, the calculations indicated that, on average, across all 15 tractor/home combinations measured at Coldwater, the percentage of home weight resting on the tractor ball hitch was approximately 24%. That is, 24% of the home weight, on average, was being carried by the tractor unit. The remaining 76%, on average, was being carried by the axle sets under the home unit.

This particular number is important for subsequent analyses related to the dynamic handling and braking performance of such vehicles under highway conditions. It also plays a role in their low-speed turning ability at intersections. This load-sharing number is referred to in subsequent sections of the report as "hitch load percentage."

The hitch load percentage can also be easily estimated from the rearward location of the axle set under the home unit, provided that the weight of the home unit is known to be uniformly distributed over its length. In general, this is assumed to be the case. However, independent estimates of hitch loads, based upon the axle loads measurements, help to confirm the simpler estimates and to illustrate the potential range of load variations seen in actual tractor/home combinations.

Supplementary Information from the Michigan Department of Transportation (MDOT) and the Manufactured Housing Association

Hitch Load Percentages

Measurements performed in 1991 by MDOT in Kent County on a representative 16-ft x 79-ft tractor/home combination (as depicted earlier in Figure 2-1) also suggest a value of 24% for the hitch load percentage. Other information from a manufacturer of 14-ft wide and 16-ft wide homes in Michigan shows that a general design rule for locating axles is to place the centerline of the axle-set two-thirds of the home length behind the front of the home. Using this rule and a 3-ft long tongue extension from the front of the home, the hitch load percentage design value is approximately 24%. These values agree well with the State Police average weigh-scale estimates indicated in the previous discussion. Consequently, a hitch load percentage of 24% was used as the baseline value in the subsequent computer analyses seen in Sections 4 - 6. (This value was also varied in those same analyses to examine certain system sensitivities.)

Home Weights

Other information from one particular home manufacturer shows that weights for their homes typically range in density from 19 psf (pounds per square foot) to 25 psf, depending upon the type of roofing and siding material used. Homes with metal roofs and metal siding were in the 19 psf range; homes with shingled roof and wood siding were approximately 25 psf. Accordingly, a 14-ft wide by 70-ft home with metal materials would weigh approximately 14 x 70 x 19 psf = 18,600 lb. Likewise, a 16-ft wide by 80-ft long home with a shingled roof and wood siding would weigh approximately 16 x 80 x 25 psf = 32,000 lb. These design values also closely approximate the range of home weights observed in the State Police weigh-scale measurements seen in Tables 2-1 and 2-2. Based on these values, an average home weight density of approximately 22 psf was used to scale home weights for many of the computer calculations seen later in Sections 4 - 6.

Number of Axles on Home Unit

The design rule used by one home manufacturer for determining the number of axles on the home unit is to compute the ratio of home suspension weight (total home weight - tongue weight) to 6000 lb and then round up to the nearest integer. For example, a home having a total weight of 28,000 lb and a tongue load percentage of 24% (or 6720 lb), would require (28000 - 6720) / 6000 = 3.5 or, rounding up to the nearest integer, 4 axles. The measured data in Tables 2-1 and 2-2 by and large follow this pattern.

3.0 Findings from Field Study Observations and Videotaping

The field study was designed to gather data on the behavior of both the tractor/home unit and the behavior of vehicles as they pass the tractor/home unit. The focus of the field study was to determine if the behavior of tractor/home units and vehicles passing tractor/home units differed between 14-foot wide and 16-foot wide home units. As will be described in greater detail later, a vehicle equipped with a videotape unit followed behind the escort vehicle that followed behind the tractor/home unit. The videotape equipment in the observation vehicle generated a complete video record of each home delivery observed. In addition to the videotape record, observers in the observation vehicle recorded behaviors of the tractor/home unit (i.e., lane encroachment) and vehicles passing the tractor/home unit (i.e., shoulder encroachment of passing vehicles) during the trip on multilane divided highways. Videotape and observation data were collected for a total of six deliveries of 14-foot wide home units and seven 16-foot wide home units.

General Data Collection Protocol

Two identically configured vehicles were used for the observations (Figure 3-1). Each data collection trip began with the observation vehicle travelling to the rest area on northbound I-69 located north of the Michigan-Indiana border, immediately south of I-94. Observers waited at this rest area until a tractor/home unit of appropriate size (i.e., 14-foot or 16-foot wide) was seen approaching from the south. Once the tractor/home unit was observed approaching, the observation vehicle positioned itself behind the escort vehicle that followed behind the tractor/home unit. At this time the observers started the video camera recording unit and completed the background data collection sections of the Route Log Sheet (see Appendix C) and the Log Sheet for Vehicle Passing (see Appendix D).

The video camera was positioned in the camera mount (Figure 3-2) so the view in the video monitor (Figure 3-3) was filled by the roadway and rear of the tractor/home unit. The field of view extended from the outside of the left shoulder to the outside of the right shoulder, the camera lens focused at infinity. In addition to the view of the roadway and tractor/home unit, the videotape was coded with the time the observation was made (hour, minute, second of real time). This time stamp allowed linkages between the data recorded on the observation data sheets and the videotape record of the trip. For example, as the tractor/home unit changed road segments (e.g., turned off of N.B. I-69 onto E.B. I-94) this change was recorded on the Route Log Sheet. The observer recorded not only the new

Figure 3-1. Observation Vehicle.

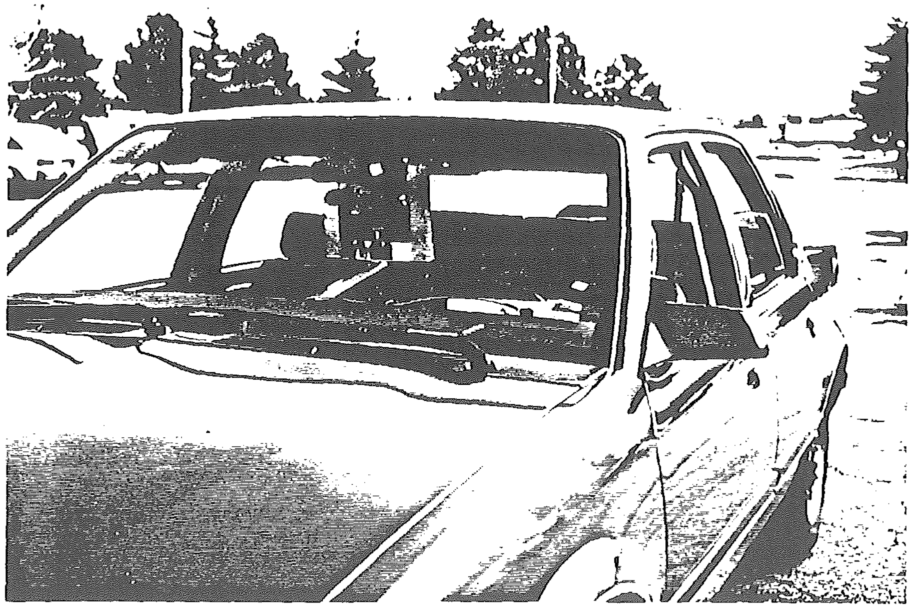


Figure 3-2. Video Camera and Vehicle Mount.

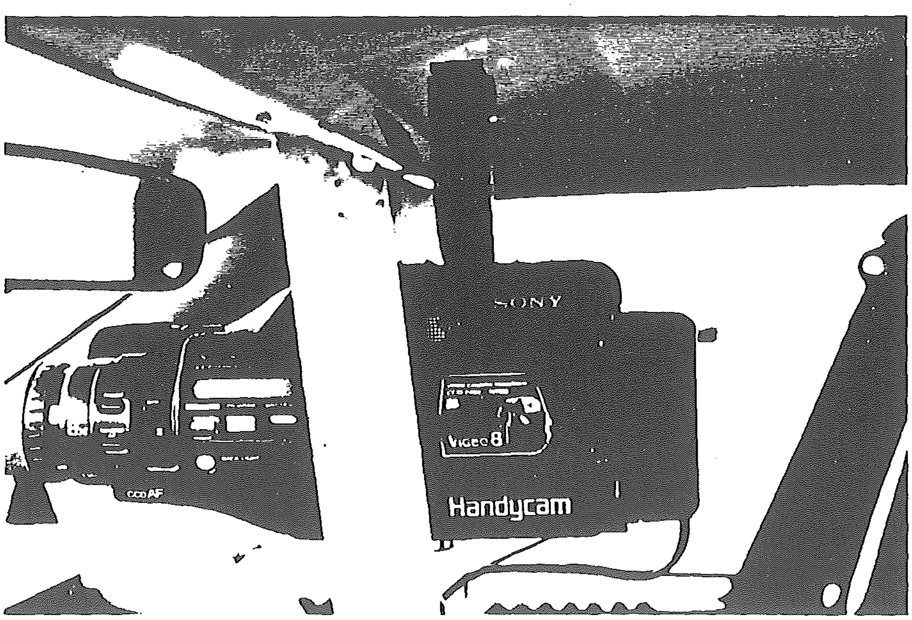


Figure 3-3. Video Monitor and Timer Display (foreground).

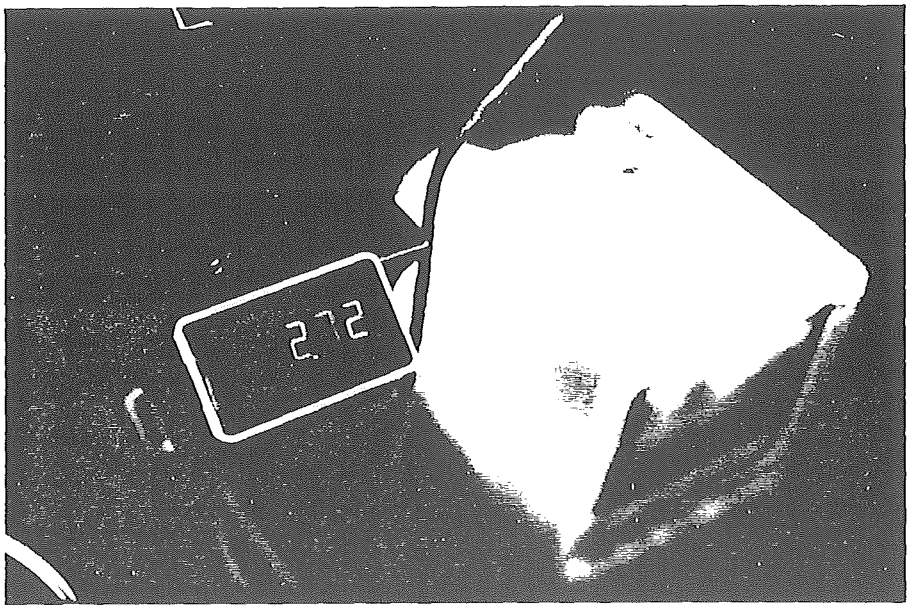
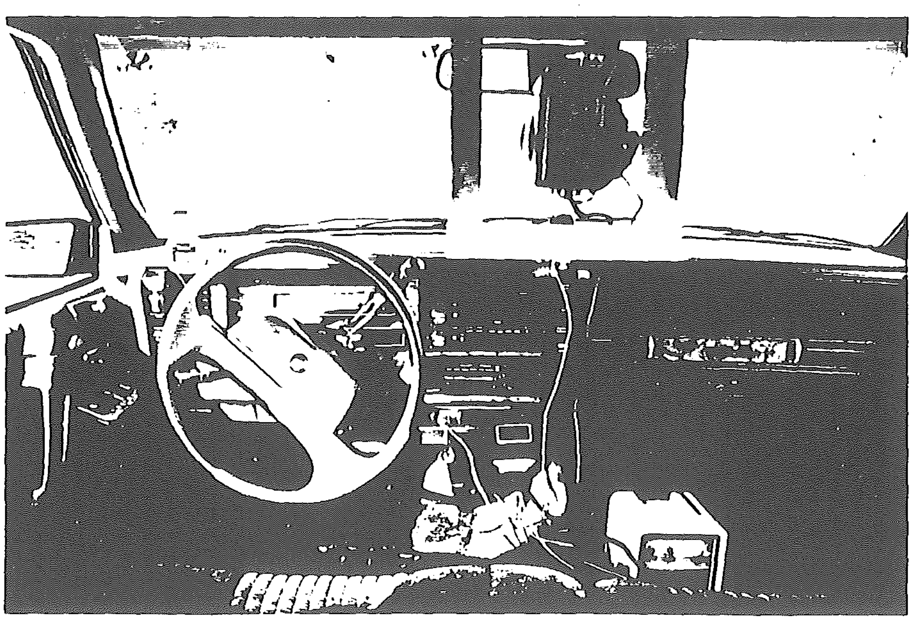


Figure 3-4. Total Data Collection Apparatus in Vehicle.



route segment (in this case E.B. I-94), but also the time the route change took place. By comparing the Route Log Sheet time with the time stamped on the videotape, observers are able to identify the specific road segment the tractor/home unit is travelling on in the videotape. Figure 3-4 shows the entire data collection apparatus in the observation vehicle. Specific data collection protocols for each behavior observed in the project are described with study results and a discussion of the findings in the following sections.

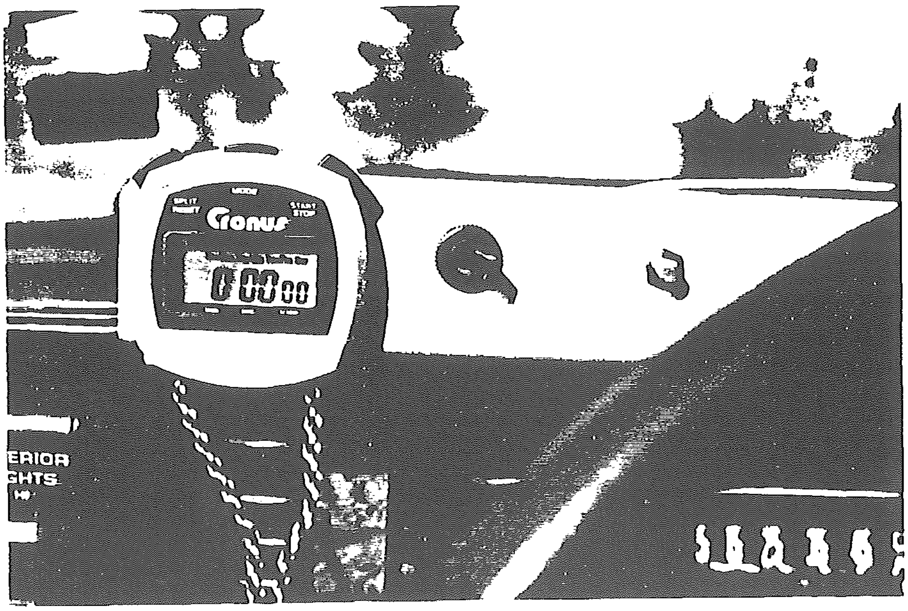
Tractor/Home Unit Positioning

The goal of this portion of the study was to examine if 16-foot wide tractor/home units encroach into the adjoining lane of roadways more than 14-foot wide units. The results examined in this analysis describe behavior on freeways and multilane divided highways (12-ft lanes) having wide and well maintained shoulder characteristics, in general. Data have been fully gathered from the videotape record and analyzed for encroachment behavior of the tractor/home units on 2-lane undivided roadways. These data are reported later in Section 3.0.

Data Collection Methods

Encroachment time of the tractor/home unit was measured by the driver of the observation vehicle using the timing apparatus shown in Figure 3-5. Encroachment of the tractor/home unit was recorded only when a vehicle or platoon of vehicles began to attempt to pass the tractor/home unit. This procedure was used because tractor/home encroachment is of little safety consequence unless vehicles are attempting to pass. Encroachment was measured in discrete "events." An event was considered to be the period of time a vehicle or platoon of vehicles traveled from the front of the observation vehicle (passing maneuver initiation) to the front of the towing tractor (passing maneuver end, see Figure 3-6). Tractor/home unit encroachment was defined as the period of time any portion of the left edge of the tractor/home unit was observed to be over the center (dashed) line. As a vehicle approached the tractor/home unit in the passing lane, the stopwatch (used to record total event time) was started. Encroachment time was measured using a timer engaged by the switch on the timing apparatus panel (Figure 3-5). When the tractor/home unit was over the center line the switch was engaged in the left position (mimicking the movement of the tractor/home unit), starting the timer. When the tractor/home unit returned to the proper lane, the switch was returned to the right position, stopping the timer. This procedure was repeated as many times as the tractor/home unit swayed over and back across the center

Figure 3-5. Timing Apparatus.



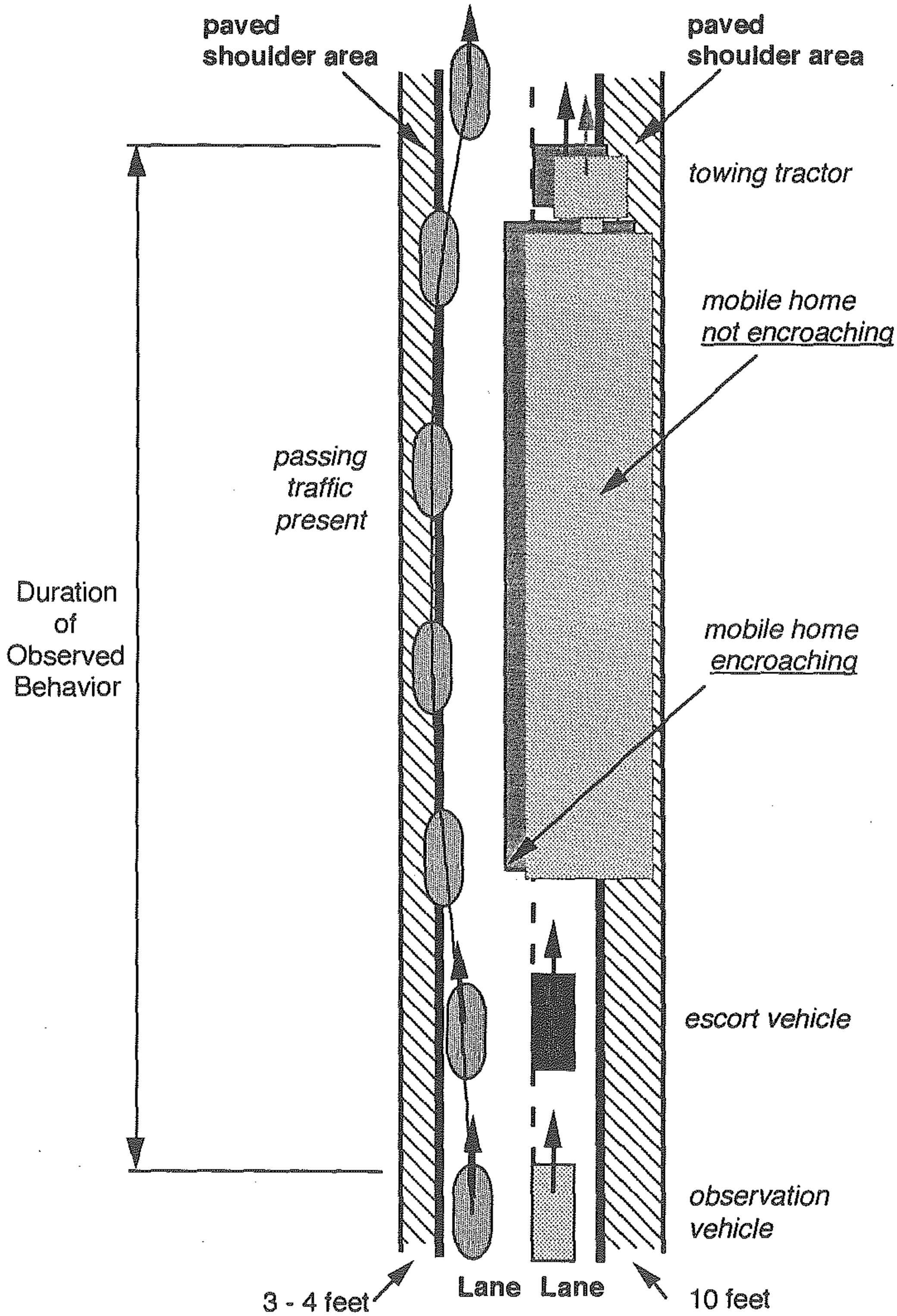
line. The switch timer recorded the total time the tractor/home unit was over the center line during the passing "event." When the last vehicle in the passing platoon completed the pass (i.e., passed beyond the front of the towing tractor), the total stopwatch time and time out of lane was recorded on the Log Sheet for Vehicle Passing. Once the data was recorded on the data sheet, the stopwatch was zeroed out using the timer-clear button on the stopwatch and the time on the encroachment timer was cleared using the button on the timing apparatus panel.

Results

Data recorded in the field were converted into the proportion of time the tractor/home unit was encroaching during each event by dividing the total event time (from the stopwatch) by the encroachment time from the timer. Each of the encroachment time analyses described in the following section uses this proportion as the dependent variable.

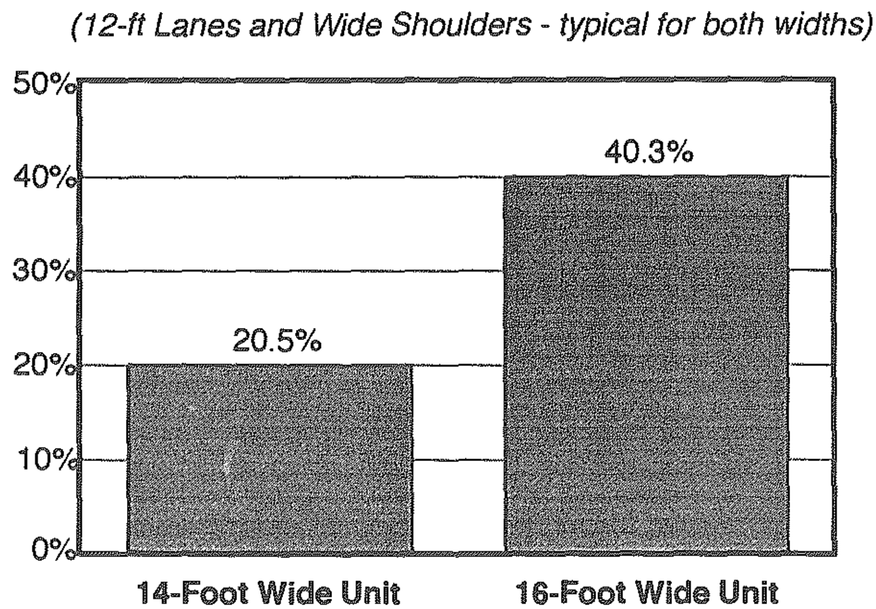
The data show that during passing events 16-foot tractor/home units encroached into the passing lane more than 14-foot units on average. Specifically, 16-foot units were observed encroaching an average of 40.3% of the time for each passing event, while

Figure 3-6. Encroachment Behavior by Mobile Home When Passing Traffic is Present — Multilane Highways.



14-foot units were observed encroaching an average of only 20.5% of the time for each passing event (see Figure 3-7). In other words, 16-foot wide units encroached into the passing lane during passing events twice as much as did 14-foot units.

Figure 3-7. Tractor/Home Encroachment Proportion of Time Encroaching in Passing Lane (Multilane Divided Highways)

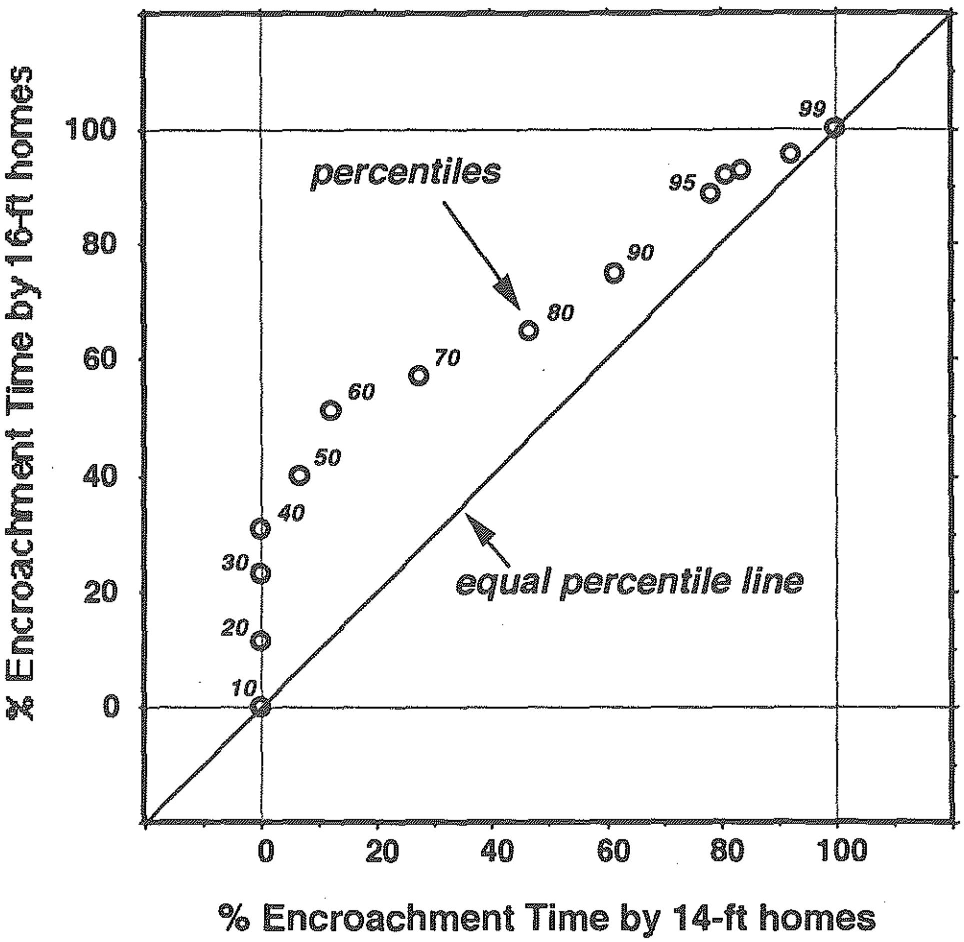


There was a good deal of variation, however, between the encroachment behavior of individual tractor/home units. That is, some tractor/home drivers encroached into the passing lane significantly less than other drivers. The range of average encroachment (over an entire delivery trip when adjoining traffic was present) for 16-foot units was from a low of 3.4% to a high of 60.9%. The range of average encroachment (over an entire delivery trip) for 14-foot units was from a low of 2.3% to a high of 54.3%.

Another way to examine the encroachment data is to examine the entire range of encroachment time proportions. Figure 3-8 shows the relative percentiles of encroachment proportions for both 14-foot and 16-foot units plotted. Figure 3-8 shows that 14-foot units did not encroach into the passing lane in 40% of all passing events, but 16-foot units did not encroach into the passing lane in only 10% of all passing events. Taken as a whole, this figure emphasizes the finding that 16-foot wide units encroach into the passing lane more than do 14-foot units.

Figure 3-8. Percentile Comparison of Encroachment Times for 16-ft versus 14-ft Wide Mobile Homes

[On-Highway Measurements]



Summary

The preceding analyses show that 16-foot wide tractor/home units are more likely to encroach into the passing lane while they are being passed by other vehicles on multilane divided highways than are 14-foot units. While these encroachments degrade the level of safety on these roadways, the level and effect of this degradation is unclear. One way to examine the significance of the effect of these encroachments on safety is to examine the behavior of the drivers attempting to pass the tractor/home units. One would expect that passing vehicles would be forced onto the shoulder of the roadway more often by the 16-foot units because these units are encroaching into the passing lane more. However, this is an empirical question that can be answered by data described in the following section.

Note that these preceding analyses describe encroachment behavior of tractor/home units on multilane divided highways only. Data on encroachment behavior on 2-lane undivided roadways is described later in Section 3.0.

Shoulder Use of Vehicles Passing Tractor/Home Units

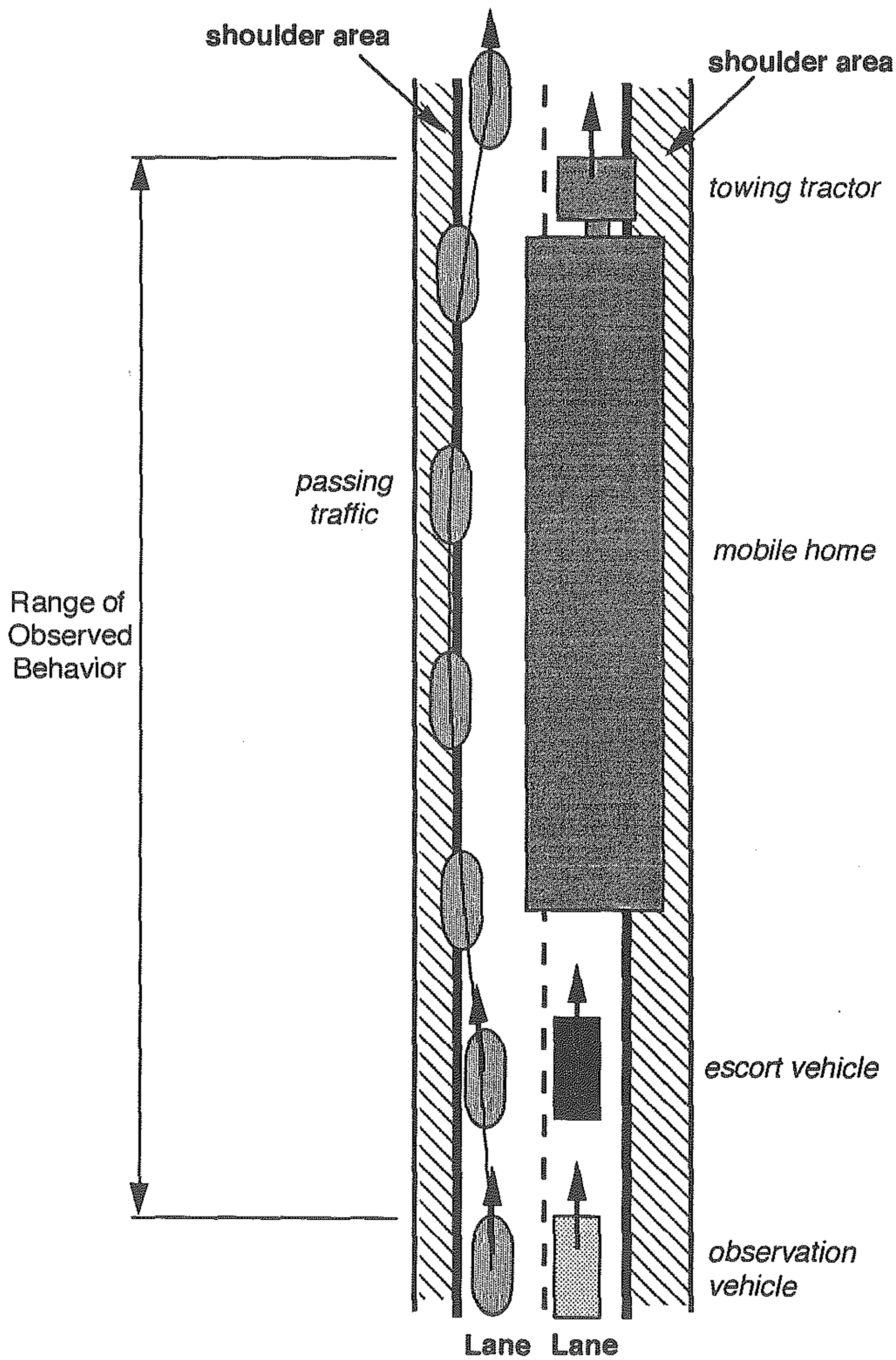
The goal of this portion of the study was to examine if vehicles passing 16-foot wide tractor/home units use the shoulder of the roadway during the passing maneuver more often than vehicles passing 14-foot wide units. Data were collected for passing behaviors on both multilane divided highways and 2-lane undivided roadways.

Passing Behavior on Multilane Divided Highways

Data Collection Methods

Shoulder use of passing vehicles was measured by the driver or observer seated in the front passenger seat of the observation vehicle. Data were recorded on the Log Sheet for Vehicle Passing (Appendix E). A vehicle was targeted for observation when it pulled even (in the passing lane) with the front of the observation vehicle. For each vehicle (or the first vehicle in a platoon of passing vehicles), the observer recorded the time from the video camera monitor on the Log Sheet (for data linkage purposes). The general scheme for shoulder use observations is shown in Figure 3-9. A vehicle was considered to have used the shoulder when one of that vehicle's left (driver) side tires crossed completely over the edge line marking the shoulder. A tire was considered to be completely over the edge line if the observer could see unmarked pavement between the inside of the left side tire and the left edge of the edge line. If the left side tires remained on the edge line, but did not cross completely over, the vehicle was considered to have not used the shoulder. A vehicle was considered to have encroached onto the shoulder if the left side tires passed across the edge line at any point in the range of observed behavior (Figure 3-9). In order for a vehicle to have been considered not to have used the shoulder, that vehicle had to remain on or to the right of the shoulder edge line while within the range of observed behavior described in Figure 3-9.

Figure 3-9. Shoulder Usage by Passing Traffic on Multilane Divided Highways.



Results

As shown in Table 3.1, passing vehicles were more likely to use the shoulder than not use the shoulder when passing either 14-foot and 16-foot wide units. However, this table shows little apparent difference in the shoulder use behavior of passing vehicles between 14-foot and 16-foot wide units.

Table 3.1

Number of Passing Vehicles Using the Shoulder — by Tractor/Home Unit Width (on Multilane Divided Highways)

Frequency Column Percent	14-Foot Wide	16-Foot Wide
Did Not Use Shoulder	103 40.6%	186 38.5%
Did Use Shoulder	151 59.4%	297 61.5%

Summary

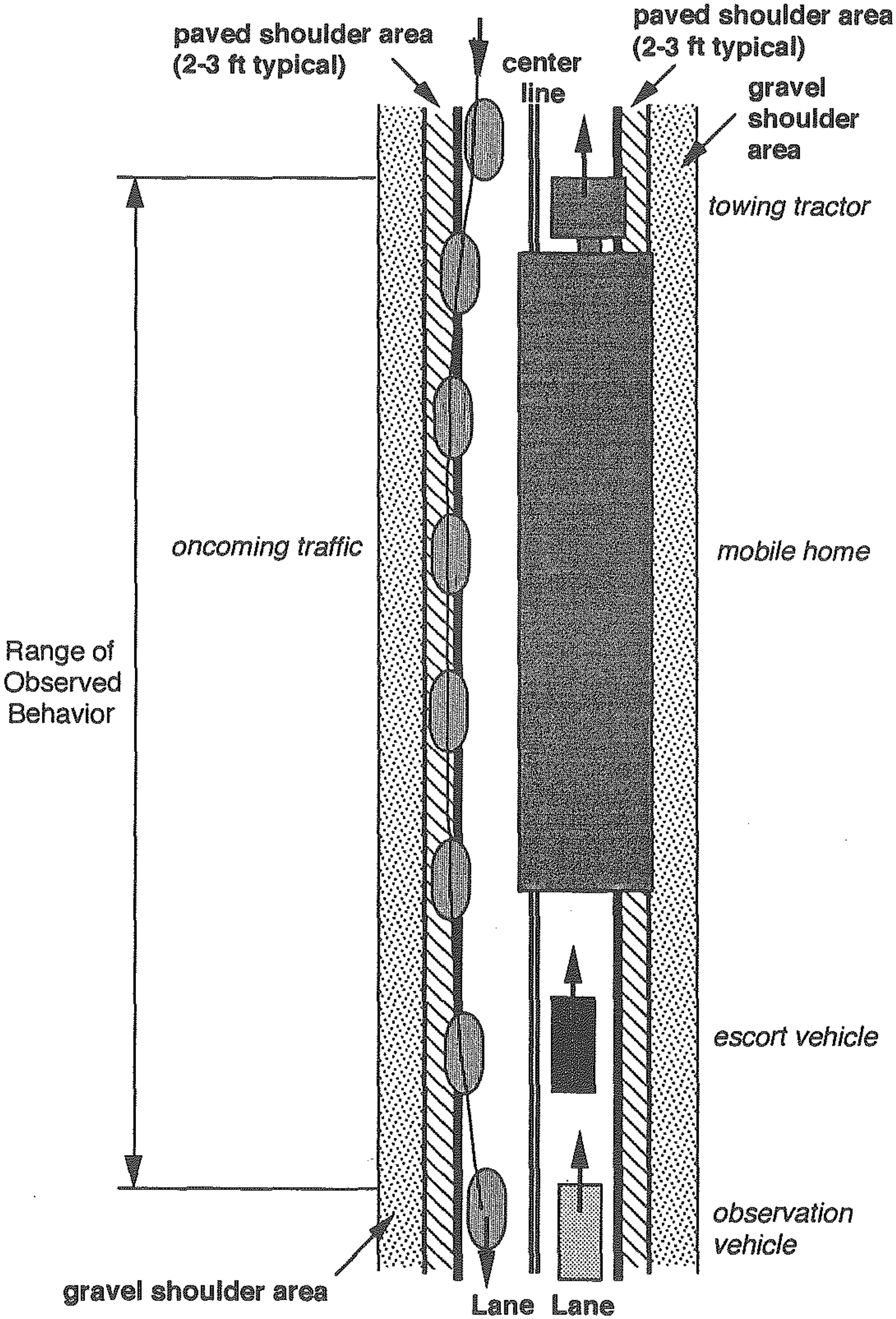
Despite the earlier finding that 16-foot wide tractor/home units encroached into the passing lane more than 14-foot wide units (when vehicles were passing), no relationship was found between the shoulder use behavior of passing vehicles and the width of the tractor/home unit being passed. This finding further muddles the question of the safety impact of permitting the 16-foot units on the road. That is, while intuitively it would seem that if tractor/home units encroached more into other lanes and that these encroachments would have a detrimental effect on the ability (or desire) of passing vehicles to remain in their lane, this was not found to be the case. In fact, passing vehicles (on multilane divided highways) were found to use the shoulder nearly two-thirds of the time regardless of the width of the tractor/home unit being passed. This finding does not support the contention that 16-foot wide tractor/home units degrade the safety of drivers travelling around those units more than do 14-foot wide units. However, these findings do suggest that both 14-foot and 16-foot units degrade the safety of vehicles trying to pass those units. This degradation of safety is based on the fact that vehicles are using the shoulder to complete passing maneuvers rather than the travel lanes. Use of the shoulder decreases the margin of error available to vehicles passing the homes. In addition, shoulder surface conditions are often much poorer than the normal travel lane, thereby increasing the chances of vehicle control problems for vehicles using the shoulder.

Oncoming Vehicle Behavior on 2-lane Undivided Roadways

Data Collection Methods

Shoulder use of vehicles approaching the tractor/home unit in the oncoming lane on 2-lane undivided roadways was measured by observers viewing the videotape log of the trips. A vehicle was targeted for observation when it pulled even (in the oncoming lane) with the front of the tractor/home unit. The general scheme for shoulder use observations is shown in Figure 3-10. A vehicle was considered to have used the shoulder when one of that vehicle's right (passenger) side tires crossed completely over the edge line marking the shoulder. A tire was considered to be completely over the edge line if the observer could see unmarked pavement between the inside of the right side tire and the right edge of the edge line. If the right side tires remained on the edge line, but did not cross completely over, the vehicle was considered to have not encroached onto the shoulder. A vehicle was considered to have used the shoulder if the right side tires passed across the edge line at any point in the range of observed behavior (Figure 3-10). In order for a vehicle to have been considered not to have used the shoulder that vehicle had to remain on or to the left of the shoulder edge line while within the range of observed behavior described in Figure 3-10.

Figure 3-10. Shoulder Usage by Oncoming Traffic on Two-Lane Highways.



Results

As shown in Table 3.2, passing vehicles were more likely to use the shoulder than not use the shoulder when approaching 16-foot wide units.

Table 3.2

Number of Oncoming Vehicles Using the Shoulder — by Tractor/Home Unit Width (on 2-lane Undivided Roadways)

Frequency Column Percent	14-Foot Wide	16-Foot Wide
Did Not Use Shoulder	79 67.5%	219 42.9%
Did Use Shoulder	38 32.5%	291 57.1%

Summary

The findings of shoulder use behavior of oncoming vehicles on 2-lane undivided roadways differ somewhat from those from multilane divided highways. That is, no difference in shoulder use was found for vehicles passing 14-foot versus 16-foot wide tractor/home units on multilane divided highways (although a majority of drivers passing 14-foot or 16-foot wide units used the shoulder), but a noticeable difference in shoulder use was found between vehicles approaching 14-foot versus 16-foot wide units in the oncoming lane on 2-lane undivided roadways. Drivers passing by an oncoming 16-foot wide tractor/home unit were more likely to use the shoulder than were drivers passing by oncoming 14-foot wide units. In fact, while 57% of drivers used the shoulder when passing by an oncoming 16-foot wide unit, only 32% of drivers used the shoulder when passing by an oncoming 14-foot wide unit.

What is clear is that the shoulder use of vehicles on 2-lane undivided roadways represents a reduction of safety. In many of the shoulder use events on 2-lane undivided roadways, observed drivers chose to move off of the paved road surface onto an unpaved shoulder area. The drop-off from and return to a paved road surface is a potentially hazardous vehicle maneuver that should generally be avoided because it can lead to loss of control. In addition, driving on an unpaved surface is generally more hazardous than driving on a paved surface because of reduced tire friction and the uneven surface. This type of behavior by passing drivers — to utilize unpaved shoulder areas — was far less frequent on freeways.

Speed of Tractor/Home Units

The goal of this portion of the study was to examine the speeds that each of the tractor/home units traveled at during their trip.

Data Collection Methods

Once the observation vehicle caught up with the tractor/home unit and achieved a steady speed, the passenger seat observer queried the observation vehicle driver to determine the speed at which the vehicle was travelling. The driver reported the speed from the observation vehicle speedometer to the nearest five mile per hour level. The passenger seat observer then held a prepared flash card up in front of the video camera to record the speed. This query and record system was repeated every five (5) minutes throughout the trip. The speed data were transcribed from the videotape later by another observer who recorded not only the speed of travel (from the flash card) but also the road type (i.e., multilane divided highway, multilane undivided roadway, two-lane undivided roadway).

Results

Results from the speed observations are summarized in Table 3.3. The speed limit for such vehicles is 45 mph on highways with 4 or more lanes and 35 mph on highways with less than 4 lanes. As shown in the table, vehicles of both widths consistently drove in excess of the speed limit prescribed on their travel permits. There was no difference between the average speeds of 14-foot versus 16-foot units.

Table 3.3

Speed of Tractor/Home Units
by Tractor/Home Unit Width and Roadway

Number of Observations Average Speed	14-Foot Wide	16-Foot Wide
Multilane Divided	109 54.9 mph	127 54.1 mph
Multilane Undivided	None	1 45.0 mph
Two-lane Undivided	5 51.0 mph	30 51.2 mph

Summary

These data show that tractor/home units of both widths regularly travel in excess of the maximum speed specified on their travel permits. 16-foot wide units were found to be travelling at almost exactly the same average speeds as the 14-foot wide units; however, the effects of this speeding behavior on safety may differ between the units. The specific effects of this speeding behavior on the safety of the tractor/home units and on the traffic that must interact with the units is unclear. Some may argue that the higher tractor/home unit speeds simply act to reduce the speed variance on the roadway and thus actually improve safety. On the other hand, these units are in clear violation of their lawful permit. In addition, the dynamics of the tractor/home units stability can be affected negatively by the higher travel speeds observed.

Further Videotape Analyses Addressing Issues Raised Since the Interim Report

Analysis of adjoining lane encroachment and right shoulder use of homes.

In the interim report, adjoining lane encroachment behavior was estimated by taking the average of the proportion of time the home units were encroached into the adjoining lane during each passing event. In the subsequent analyses discussed in this section we calculated encroachment time a bit differently. The results of the first calculation resulted in events of different duration receiving equal weight in the average encroachment time. That is, a given event of 130 seconds duration in which the home unit was encroached into the adjoining lane 40% of the time was given the same weight in the encroachment average as an event of only 30 seconds duration. Thus, if there were differences in encroachment behavior that may be moderated by the event duration, these differences would be overlooked using the event-based encroachment average. In the following analyses of encroachment, the proportion of time the homes were observed to be encroaching into the adjoining lane was calculated by taking the total time that a specific home encroached into the adjoining lane during all passing events and dividing this sum by the total time of all passing events for that home. Using this calculation, all passing events are given equal weight in proportion to their duration.

In this section we describe further data analyses on home encroachment into the adjoining lane and right shoulder use by the home by lane width, shoulder condition, and whether the homes were travelling on multilane divided highways (the passing events in which traffic was travelling in the same direction as the home and was overtaking the home) or two-lane roadways (events in which vehicles were passing the home in the oncoming direction as they approached and passed the home travelling in the opposite direction). Due to the relatively small number of homes observed (i.e., six 14-foot wide homes and seven 16-foot wide homes), we believe it is best to describe the data in terms of a case study rather than to try to apply inferential statistics to the data. In this way, relationships can be examined as a whole without the confusion that would be caused trying to interpret the meaning of statistical values based on tests without sufficient statistical power to be meaningful because of small sample sizes.

Data Collection Methods

Data collected subsequent to the interim report were gathered by observations of the videotape logs made in the fall observations. Data were collected for each passing event.

A passing event, for traffic overtaking the tractor/home, was defined as beginning when the passing vehicle comes into view on the video monitor and ending when the vehicle has cleared the front of the tractor towing the home. The end of a passing event was usually easily determined from the position of the passing vehicle in relation to the shadow of the tractor on the road. On those occasions when the road curved to the right and the view of the overtaking vehicle was blocked by the tractor/home, the passing event was considered to have ended when the overtaking vehicle was eclipsed by the tractor/home. For oncoming traffic, a passing event was defined to begin when an oncoming vehicle was even with the front of the tractor/home and the event end was defined when the vehicle passed out of view in the monitor. As above, if the road curved to the right, the passing event started when the oncoming vehicle was no longer blocked by the tractor/home. If a queue of vehicles was passing the tractor/home, the passing event was ended when the last vehicle passed from view.

Use of the right shoulder was defined as occurring when the right wheels of the home were to the right of the fog line and on the shoulder of the road. Encroachment to the left (adjoining) lane was defined as occurring when the left edge of the home was to the left of the line marking the edge of the lane the home was travelling in. A variety of clues could be identified that indicated lane encroachment and shoulder use; how these clues were interpreted as indicating lane encroachment or shoulder use often depended on the width of both the home and the traffic lane. Also, because of the limits of the resolution of the TV monitor, there was occasional difficulty in recognizing the beginning or ending of encroachment or shoulder use. Therefore, the methods used for determining encroachment were chosen to be a conservative measure of excursions from the lane proper.

16' Wide Homes - 12' Wide Traffic Lanes.

It was possible to determine right shoulder use and adjoining lane encroachment from either side of the home. Viewing the right side of the home, the home was considered to have been using the right shoulder when the right wheel of the undercarriage was to the right of the fog line. Encroachment into the left (adjoining) lane could also be determined from the position of the right wheel of the undercarriage relative to the fog line. When the right wheel of the home unit was to the left of the fog line the home was considered to be encroached to the left. When this wheel was on the fog line no encroachment was considered to be taking place. As long as the right wheel is visible, this was the easiest way to determine the position of the home relative to its travel lane.

On the left side of the home, the lateral distance from the edge of the home to the outside of the left tire is about 3'. There are usually several places on a tape, where the position of the chase vehicle is such that we could observe the position of the right wheels of the home to determine if the wheels were on or near the fog line. After some practice viewing of the tapes, it was possible to develop a good sense of what this distance looks like when encroachment is occurring on either side. When this distance appeared to be less than 3' the home was considered to be encroached to the left. When this distance appeared to be greater than 3' the home was considered to be travelling on the right shoulder. However, care should was taken in using the left side of the home to determine encroachment. The zoom lens on the video camera was positioned well into the telephoto range resulting in a foreshortening of the field of view resulting in a parallax angle between the camera, mounted in the center of the car, and the edge of the home. Because of this parallax angle the home may appear to be encroached to the left when it is not. Also, the shadows from the home and wheel can obscure this area and make this 3' distance appear much smaller than it was. Thus, all observations of home placement in the lane were based upon the best estimate of the observers using all available placement cues rather than precise measurements of lane edgings or axle width.

Traffic Lanes Other Than 12' Wide.

On 11' traffic lanes it was possible for a 16' wide home to be using the right shoulder and also be encroaching into the adjoining left lane at the same time. On the right side of the home, use of the right shoulder was determined in the same manner as described earlier for 12' lanes. In these cases, however, when the right wheel was just off (about a foot or so) the right of the fog line, the home was considered to be encroached to the left.

On the left side of the home, encroachment to the left adjoining lane was determined in the same manner as described above for 12' lanes. In these cases, however, when the left edge of the left wheel appeared to be about two feet to the right of the center line, the home was considered to be travelling on the right shoulder. Eleven-foot and 12-foot were the most common lane widths of roadways used by homes during our observations. As described earlier, events can be found on the tape where the view of the home wheel(s) and fog and center lines are not blocked by the chase vehicle, and the position of the home while using the right shoulder and/or encroachment into the left adjacent lane can be observed. On a few occasions, other lanes widths were found that required similar adjustments.

14' Wide Homes - 12' Wide Lanes.

Viewing the right side of the home, use of the right shoulder was the same as with 16' wide homes. However, because of the two foot difference in width, the home will not be encroached to the left until the right wheel of the home is about one foot to the left of the fog line. On the left side of the home, encroachment to the left will not begin until the left wheel is about 2' right of the center line. Use of the right shoulder will not begin until the left wheel is more than about 3' to the right of the center line.

Traffic Lanes Other Than 12' Wide.

On 11' traffic lanes and viewing the right side of the home, use of the right shoulder remains the same while encroachment to the left adjacent lane begins when the right side home wheels are just to the left of the fog line. Viewing the left side of the home, use of the right shoulder begins when the left home wheel is more than about 2' from the center line. Similar adjustments were made for other traffic lane widths.

Measuring Encroachment Time

A computer program (ABTIMERS) was written to record shoulder use and adjoining lane encroachment times as determined by one or two observers. ABTIMERS begins by prompting for the tape identification number and number of observers. This information is stored with each file. ABTIMERS then prompts for the file name. The file name begins with "L" or "R" depending on whether left or right encroachment is being measured and is followed by a six digit number, the event start time. Left adjoining lane encroachment was always measured first. Next, the program prompts for the total event time in seconds (this was determined in the original set of field observations). ABTIMERS then prompts for any keyboard input to begin recording encroachment data. At this point a typical computer display would be:

```
SWITCH-INPUT TIMER PROGRAM
Tape ID: 141023SK121042392

Enter File Name: L112321
Enter Event Duration (sec): 12

Press any key to begin:
```

Each observer held a switch, spring loaded in the open position, which was wired to the parallel port of the PC running ABTIMERS. The videotape was played and, when the clock on the videotape showed the event start time, one of the observers pressed the space bar to begin data collection. As the tape played, each observer pushed his button when he believed encroachment (shoulder use) was taking place and released it when the encroachment (shoulder use) stopped. ABTIMERS recorded: the position (open or closed) of both switches every 1/10 of a second, the total time each switch was closed, and the number of switch transitions (closings and openings), and then the program signaled the end of the event with a beep to signal the end of data collection. As an example, the computer then displays the data, to the nearest second, as follows:

```
SWITCH-INPUT TIMER PROGRAM
Tape ID: 141023SK121042392

Collected for 12 sec
A & B Timer Totals
--------------------------

A pressed      5 sec
B pressed      5 sec
Both A & B      4 sec
Not A or B     7 sec
A X-itions     2
B X-itions     2

Save Data to L112321  (Y/N) ?
```

This display shows the total number of seconds each observer had their switch depressed, the number of seconds both observers and neither observer had their switches depressed, and the number of times each observer pressed and released his switch. If an "N" is entered, or if "Esc" is pressed to abort the event, ABTIMERS returns to the file name and event duration inputs. These can be changed if necessary and the data collection begun again. If "Y" is entered the data are saved and the computer displays:

```
SWITCH-INPUT TIMER PROGRAM
Tape ID: 141023SK121042392

Enter File Name: R112321
Enter Event Duration (sec): 12

Press any key to begin:
```

The procedure is then repeated for right shoulder use.

Road Type, Lane and Shoulder Conditions.

To identify road type, as well as to identify lane and shoulder conditions from the 1990 Sufficiency Rating [3], federal and/or state designations for each road were noted from the written videotape logs. Also, longer road sections were sometimes divided at major intersections as a way making specific road sections more easily identified to determine road characteristics in the second viewing. The result was a road list with each road section designated by a two digit number and defined by its beginning and end points and the direction of travel, i.e. 04. I-96 WB between M- 43 and US-27. Lane and right shoulder width, left and right shoulder condition data were gathered from the 1990 Sufficiency Rating: Michigan State Trunkline Highways (1990 S.R.) and from tape observations as follows:

Two lane undivided roads - Lane width, right shoulder width, and left and right shoulder condition were obtained from the 1990 S.R. Codes were added for no shoulder (curb, weeds, dirt, grass) and for road construction.

Multiple lane undivided roads - Lane width and right shoulder width and condition were obtained from the 1990 S.R. Codes were added for no shoulder (curb, weeds, dirt, grass) and for road construction. The left shoulder was always 2 or 3 lanes away and judged not to have any effect on overtaking, passing traffic. This was coded separately.

Multiple lane divided roads - Lane width and right shoulder width and condition were obtained from the 1990 S.R. Codes were added for no right shoulder (curb, weeds, dirt, grass) and for road construction. On these roads the left shoulder was defined as the shoulder to the left of the lanes of travel of the tractor/house. On interstates or limited-access highways the left shoulder was a 2-foot wide strip of pavement. On other multiple lane divided roads without limited access the shoulder could have other characteristics and codes were added for these.

On a very few occasions, when the videotape showed conditions obviously different from those in the 1990 Sufficiency Rating and both observers agreed, information on the road conditions from the tapes was recorded.

Results

Based on a reanalysis of the data collected on left adjacent lane encroachment by observers in the field (using the total left encroachment time divided by the total event time over all events for each home), we found that 16-foot wide homes encroached into the left adjoining lane more often than did 14-foot wide homes (43.9% [n=6][1] of the time for 16-foot wides versus 31.0% [n=5] for 14-foot wides). While the absolute proportions of time encroached using this analysis strategy differs from the previous analysis, these results are consistent in that we found 16-foot homes to have encroached into the adjacent left lane more often than 14-foot homes.

The remainder of the results described in this section are the result of the observations made from the videotape as described earlier. The data show that while both 16-foot and 14-foot homes use the right shoulder a majority of the time, 16-foot homes use the right shoulder a greater proportion of the time than do 14-foot homes (80.6% [n=7] for 16-foot homes versus 55.1% [n=6] for 14-foot homes).

Effects of lane width on home lane deviations.

Homes of both widths were likely to spend less time encroaching into the left adjoining lane when travelling on roadways with 12-foot lanes than when travelling on 11-foot lanes (36.2% [n=8] overall encroachment on 11-foot wide lanes versus 10.7% [n=13] overall encroachment on 12-foot lanes). However, there was little difference in right shoulder use of homes when shoulder use was examined by lane width (67.2% [n=8] of time using right shoulder on 11-foot lanes versus 68.3% [n=13] of time using right shoulder on 12-foot lanes). There were insufficient numbers of events on roadways having other widths to conduct even a case-wise analysis meaningfully.

It appears from the following table that 14-foot wide homes were more likely to be encroaching into the left adjoining lane than 16-foot homes on 11-foot lanes, while the reverse was the case for 12-foot lanes. However, please note that a relatively small number of 14-foot homes was observed on the 11-foot lanes (i.e., n=3), and thus this may be the result of case-specific factors unrelated to the larger, more general population of vehicles.

[1] In each of the analyses in this section describing home lane deviations, the value "n =" represents the number of homes observed. For each home, a number of events were examined as described earlier in the methods.

14-foot home on 11-foot lane:	46.8% encroachment [n=3]
16-foot home on 11-foot lane:	29.5% encroachment [n=5]
14-foot home on 12-foot lane:	4.9% encroachment [n=6]
16-foot home on 12-foot lane:	15.5% encroachment [n=7]

There is also no apparent relationship between lanes of 11-foot versus 12-foot widths on use of the right shoulder when examined by home width except that 16-foot homes used the right shoulder more often than did 14-foot wide homes.

14-foot home on 11-foot lane:	27.3% right shoulder use [n=3]
16-foot home on 11-foot lane:	91.2% right shoulder use [n=5]
14-foot home on 12-foot lane:	54.8% right shoulder use [n=6]
16-foot home on 12-foot lane:	79.8% right shoulder use [n=7]

Effects of right shoulder condition on home lane deviations.

Right shoulder condition was re-coded from the description in the 1990 MDOT Sufficiency Ratings to provide larger, more inclusive categories for analysis. Despite this effort, there were only cases in which right shoulder condition was considered to be good (i.e., 1990 Sufficiency Ratings: very little deterioration, some initial deterioration not yet requiring appreciable amounts of maintenance, and occasional deterioration requiring routine maintenance) or there was no appreciable shoulder (cases of weed, dirt or grass shoulders, areas of road construction, barrels on the shoulder, broken or no pavement, drop-off, and areas with a curb but no shoulder).

Overall, homes were likely to spend more time encroaching into the left adjacent lane more often when driving on road segments with no appreciable right shoulder than when the right shoulder was in good condition (11.3% [n=13] of time encroaching on roadways with good right shoulders versus 44.4% [n=5] of time encroaching on roadways with no right shoulder). Conversely, homes were likely to spend more time using the right shoulder area when the right shoulder was in good condition than when there was no appreciable shoulder (69.0% [n=13] of time using right shoulder on roadways with good shoulders versus 43.0% [n=5] of time using right shoulder on roadways with no appreciable right shoulder).

It appears from the data that while 16-foot homes were likely to spend more time encroaching into the left adjacent lane than 14-foot wides on roadways with good right shoulders, that the opposite is true for roadways with no appreciable shoulder. Please note, however, that the number of homes observed on roadways with no appreciable shoulder is quite small, and that these results must be interpreted quite cautiously.

14-ft home on roadway with good right shoulder:	4.8% encroachment [n=6]
16-ft home on roadway with good right shoulder:	16.8% encroachment [n=7]
14-ft home on roadway with no appreciable right shoulder:	50.0% encroachment [n=2]
16-ft home on roadway with no appreciable right shoulder:	40.7% encroachment [n=3]

The data suggest that while both 16-foot and 14-foot wide homes use the right shoulder more when the roadway has good shoulders than when there is no appreciable shoulder, 16-foot homes use the right shoulder more than 14-foot homes on both shoulder conditions examined.

14-ft home on road with good right shoulder:	55.3% right shoulder use [n=6]
16-ft home on road with good right shoulder :	80.8% right shoulder use [n=7]
14-ft home with no appreciable right shoulder:	20.4% right shoulder use [n=2]
16-ft home with no appreciable right shoulder:	58.0% right shoulder use [n=3]

Effects of road type on home lane deviations.

For the purpose of the following analyses, road type was divided into two categories: (1) multilane divided highway, and (2) two-lane roadway. On the multilane divided highways events included in these analyses consisted of vehicles overtaking the homes. On the two-lane roadways, events included in these analyses consisted only of instances where oncoming traffic passed by the home (in fact there were extremely few events of vehicles overtaking homes on two-lane roadways).

Overall, homes were likely to spend more time encroaching into the left adjacent lane when travelling on two-lane roadways than on multilane divided highways (32.0% [n=7] of time encroaching into the left adjacent lane on two-lane roadways versus 10.7% [n=13] of time on multilane divided highways). While this may be due in part to characteristics of the right shoulder, this hypothesis could not be adequately explored due to the lack of sufficient data of varying shoulder characteristics for the different roadways. There was essentially no difference in use of the right shoulder between two-lane and multilane roadways (70.2% [n=13] of time using right shoulder on multilane roadways versus 68.8% [n=7] on two-lane roadways).

The data show that while 16-foot wide homes were likely to spend more time encroaching into the left adjacent lane on multilane divided highways than 14-food wides, there appears to be little difference between home widths on two-lane roadways. Please note, however, that the number of 14-foot wide homes observed on two-lane roadways is quite small, and that these results must be interpreted quite cautiously.

14-foot home on multilane divided:	5.3% encroachment [n=6]
16-foot home on multilane divided:	15.2% encroachment [n=7]
14-foot home on two-lane roadways:	36.3% encroachment [n=2]
16-foot home on two-lane roadways:	30.3% encroachment [n=5]

The data show that 16-foot homes are likely to spend more time using the right shoulder than 14- foot homes on both multilane divided and two-lane roadways. Please note, however, that the number of 14-foot wide homes observed on two-lane roadways is quite small, and that these results must be interpreted quite cautiously.

14-foot home on multilane divided:	75.8% right shoulder use [n=6]
16-foot home on multilane divided:	80.7% right shoulder use [n=7]
14-foot home on two-lane roadways:	37.1% right shoulder use [n=2]
16-foot home on two-lane roadways:	81.5% right shoulder use [n=5]

Analysis of shoulder use by passing cars and heavy trucks.

In this section we describe further data analyses on the road shoulder use of cars and heavy trucks (i.e., tractor semitrailers and doubles) as they passed the homes. Shoulder use of cars and heavy trucks is described by home width overall, and by lane width, shoulder condition, and road type. As was the case in the further analyses of the home lane deviation data, because of limited sample sizes we believe it is best to describe the data in terms of a case study rather than to try to apply inferential statistics to the data. In this way, relationships can be examined as a whole without the confusion that would be caused trying to interpret the meaning of statistical values based on tests without sufficient statistical power to be meaningful because of small sample sizes, and highly variable numbers of observations between conditions.

Data Collection Methods

Data collected subsequent to the interim report were gathered by observations of the videotape logs made in the fall observations. Data were collected for each passing event. A passing event, for traffic overtaking the tractor/home, was defined as beginning when the passing vehicle came into view on the video monitor and ending when the vehicle has cleared the front of the tractor towing the home. The end of a passing event was usually easily determined from the position of the passing vehicle in relation to the shadow of the tractor on the road. On those occasions when the road curved to the right and the view of the overtaking vehicle was blocked by the tractor/home, the passing event was considered to have ended when the overtaking vehicle was eclipsed by the tractor/home. For oncoming traffic, an event was defined to begin when an oncoming vehicle was even with the front of the tractor/home and the event end was defined when the vehicle passed out of view in the monitor. As above, if the road curved to the right, the event was not started until the oncoming vehicle was no longer blocked by the tractor/home. If a queue of vehicles was passing the tractor/home, the event was ended when the last vehicle passed from view.

Data were collected on whether or not each passing vehicle moved out of lane to pass the tractor/home. On two lane roads, for both oncoming and overtaking traffic, this meant the passing vehicle was driven across the fog line and onto the shoulder for the oncoming traffic. On multiple lane divided and undivided roads, where the passing vehicles are overtaking, this meant crossing over the fog or center line onto the shoulder/median or into the third traffic lane or left- turn lane. Traffic moving into and staying in an available third lane were not included in the passing event if the passing vehicle was not travelling in the lane immediately adjacent to the home. For single vehicle passing events, determining whether a vehicle was out-of-lane or not was most straightforward because each vehicle's tire and the fog line could be seen in the video (although the resolution of the videotape often made judgements of lane use more difficult). However, determining out-of-lane behavior of vehicles passing in queues was not always as straightforward as the case for single-vehicle events. If passing vehicles were following each other closely, the view of a vehicle's tire and the fog line was often blocked. If, in the tape observer's judgement, the lateral distance between the passing vehicle and the center line was large enough so that he was certain that the vehicle was out-of-lane, it was recorded as such. This varied according to the size of the vehicle so that a compact car would require a greater lateral distance from the center line before being considered out-of-lane than a truck would. Another clue used to determine lane placement was the degree to which the target vehicle was obscured by other vehicle(s) in the queue and the lateral distance between the lane dividing line and/or the fog line and the obscuring vehicle(s). This would also vary depending on the size of the vehicles involved.

Road Type, Lane and Shoulder Conditions.

Road type, as well as lane and shoulder conditions, was identified using the same procedures described earlier for the further analyses of the lane deviation behavior of the homes. To identify road type, as well as to identify lane and shoulder conditions from the 1990 Sufficiency Rating, federal and/or state designations for each road were noted from the written videotape logs. Also, longer road sections were sometimes divided at major intersections as a way making specific road sections more easily identified for determining road characteristics in the second viewing. The result was a road list with each road section designated by a two digit number and defined by its beginning and end points and the direction of travel, i.e. 04. I-96 WB between M-43 and US-27. Lane and right shoulder width, left and right shoulder condition data were gathered from the 1990 Sufficiency Rating: Michigan State Trunkline Highways (1990 S.R.) and from tape observations as follows:

Two lane undivided roads - Lane width, right shoulder width, and left and right shoulder condition were obtained from the 1990 S.R. Codes were added for no shoulder (curb, weeds, dirt, grass) and for road construction.

Multiple lane undivided roads - Lane width and right shoulder width and condition were obtained from the 1990 S.R. Codes were added for no shoulder (curb, weeds, dirt, grass) and for road construction. The left shoulder was always 2 or 3 lanes away and judged not to have any effect on overtaking, passing traffic. This was coded separately.

Multiple lane divided roads - Lane width and right shoulder width and condition were obtained from the 1990 S.R. Codes were added for no right shoulder (curb, weeds, dirt, grass) and for road construction. On these roads the left shoulder was defined as the shoulder to the left of the lanes of travel of the tractor/home. On interstates or limited access highways the left shoulder was a 2-foot wide strip of pavement. On other multiple lane divided roads without limited access the shoulder could have other characteristics and codes were added for these.

On a very few occasions, when the videotape showed conditions obviously different from those in the 1990 Sufficiency Rating and both observers agreed, information on the road conditions from the tapes was recorded.

Results

The data show that both cars and trucks are more likely to use the shoulder when passing 16-foot wide homes than when passing 14-foot wide homes, and that trucks were more likely than cars to use the shoulder (15.6% [n=960][2] of cars versus 35.7% [n=140] of trucks used the shoulder when passing 14-foot wide homes; 28.0% [n=1462] of cars versus 62.6% [n=131] of trucks used the shoulder when passing 16-foot homes).

Effects of lane width on car and truck road shoulder use.

Cars were more likely to use the shoulder when passing homes on roadways with 11-foot lanes than when passing homes on roadways with 12-foot lanes (49.6% [n=363] of cars used the shoulder when passing on roadways with 11-foot lanes versus 18.5% [n=2046] on roadways with 12-foot lanes). There were insufficient cases of trucks passing on lanes of width other than 12-foot to conduct even a cursory analysis. On roadways with 12-foot lanes, trucks used the shoulder 44.9% [n=247] of the time when passing.

On roadways with 12-foot lanes, cars used the shoulder more often when passing 16-foot wide homes than when passing 14-foot homes, while on roadways with 11-foot lanes there was little difference in shoulder use between cars passing 14-foot versus 16-foot homes. On roadways with 12-foot wide lanes, trucks used the shoulder more often when passing 16-foot homes.

Cars passing 14' home on road with 11-foot lanes:	51.2% shoulder use [n=41]
Cars passing 16' home on road with 11-foot lanes:	49.3% shoulder use [n=322]
Cars passing 14' home on road with 12-foot lanes:	14.0% shoulder use [n=919]
Cars passing 16' home on road with 12-foot lanes:	22.2% shoulder use [n=1127]
Trucks passing 14' home on road with 12-foot lanes:	35.7% shoulder use [n=140]
Trucks passing 16' home on road with 12-foot lanes:	57.0% shoulder use [n=107]

Effects of shoulder condition on car and truck shoulder use.

Cars were least likely to use the shoulder when passing on roadways with no shoulder (i.e., shoulders consisting of weeds, dirt or grass, road construction areas,

[2] In each of the analyses in this section on shoulder use of passing vehicles, the value "n =" represents the total number of vehicles passing. For example, in this case 960 cars were observed passing 14-ft wide homes, of which 15.6% used the shoulder.

barrels on the shoulder, broken or no pavement, drop-off, or curb no shoulder) than those with shoulders classified as "ok" (i.e., 1990 Sufficiency Ratings: 2' strip of pavement, very little pavement deterioration, some initial deterioration not yet requiring appreciable amounts of maintenance, occasional deterioration requiring routine maintenance). Furthermore, cars were more likely to use shoulders when passing on roadways with shoulders classified as "good" (i.e., 1990 Sufficiency Ratings: 3'-4' strip of pavement) than when passing homes on roadways with shoulders classified as "ok." We were able to observe a reasonable number of trucks passing homes only on roads with shoulder conditions classified as "ok."

Cars passing on road with "no" shoulder:	5.9% shoulder use [n=290]
Cars passing on road with "ok" shoulder:	24.3% shoulder use [n=2063]
Cars passing on road with "good" shoulder:	58.0% shoulder use [n=69]
Trucks passing on road with "ok" shoulder:	51.0% shoulder use [n=249]

In general, both cars and trucks were more likely to use the shoulder when passing 16-foot homes than when passing 14-foot homes on all roads regardless of shoulder condition. The only exception was that more cars passing 14-foot homes used the shoulder on roadways with shoulders in "good" condition than those passing 16-foot homes on roads with the same shoulder condition (note, however, that the total sample size was quite small). Trucks were more likely to use the shoulder when passing 16-foot homes than when passing 14-foot homes when travelling on roadways with shoulders in "ok" condition.

Cars passing 14' homes on road with "no" shoulder:	1.6% shoulder use [n=124]
Cars passing 16' homes on road with "no" shoulder:	9.0% shoulder use [n=166]
Cars passing 14' homes on road with "ok" shoulder:	15.5% shoulder use [n=802]
Cars passing 16' homes on road with "ok" shoulder :	30.0% shoulder use [n=1261]
Cars passing 14' homes on road with "good" shoulder :	70.6% shoulder use [n=34]
Cars passing 16' homes on road with "good" shoulder:	45.7% shoulder use [n=35]
Trucks passing 14' homes on road with "ok" shoulder:	38.6% shoulder use [n=127]
Trucks passing 16' homes on road with "ok" shoulder:	63.9% shoulder use [n=122]

Effects of road type on car and truck shoulder use.

Both cars and trucks were more likely to travel on the shoulder when approaching homes in the oncoming direction on two-lane roadways than when passing on multilane divided highways. As was the case in the analyses of home lane deviation, these findings may be due in part to characteristics of the right shoulder. This hypothesis could not be adequately explored due to the lack of sufficient data of varying shoulder characteristics for the different roadways.

Cars oncoming on two-lane roads:	45.2% shoulder use [n=578]
Cars passing on multilane divided:	17.9% shoulder use [n=1597]
Trucks oncoming on two-lane roads:	81.4% shoulder use [n=43]
Trucks passing on multilane divided:	45.4% shoulder use [n=207]

Cars were more likely to use the shoulder when approaching 16-foot wide homes in the oncoming direction on two-lane roadways, but their shoulder use was nearly the same when passing homes of different widths on multilane divided highways. Trucks, on the other hand, were more likely to use the shoulder when passing 16-foot homes than when passing 14-foot homes. This applied to oncoming trucks along two-lane roadways as well as to trucks passing homes travelling in the same direction on multilane divided highways.

Cars approaching 14' home on two-lane roads:	23.3% shoulder use [n=120]
Cars approaching 16' home on two-lane roads:	50.9% shoulder use [n=458]
Trucks approaching 14' home on two-lane roads:	55.6% shoulder use [n=9]
Trucks approaching 16' home on two-lane roads:	88.2% shoulder use [n=34]
Cars passing 14' home on multilane divided:	17.2% shoulder use [n=692]
Cars passing 16' home on multilane divided:	18.5% shoulder use [n=905]
Trucks passing 14' home on multilane divided:	37.7% shoulder use [n=114]
Trucks passing 16' home on multilane divided:	54.8% shoulder use [n=93]

On rare occasions, vehicles travelling in the same direction as the home unit on two-lane roads passed the home unit. Figure A.23 shows such an event. As can be seen in this figure sequence, a vehicle in the oncoming lane was forced completely onto the shoulder to avoid a collision with the vehicle passing the home unit and escorts. Passing on two-lane undivided roadways is an extremely hazardous condition because of the limited sight distance and visibility around the home and because of the amount of time required to complete the pass.

4.0 Findings on Low-Speed Turning at Intersections & Ramps

The issue of low speed turning ability, or maneuverability, of mobile homes and how such capabilities change when home width is increased is addressed within this section of the report. The analyses and calculations focus primarily upon turning scenarios at intersections. A freeway exit ramp turning example is also included.

Basic Turning Behavior

A conventional intersection geometry is used to help communicate the nature of the turning mechanics of mobile homes and the type of constraints imposed by normal highway design. To illustrate, Figure 4-1 shows an overhead view of a two-lane highway intersection. The paved road surface is assumed here to be 40 feet wide (two 12-ft lanes and two 8-ft wide paved shoulders). The intersection of the two roads is joined by circular curbs having radii of 60 feet. A time-lapse sequence of four snapshots of a mobile home (16-ft wide by 80-ft long) being towed by a tractor through the intersection in a right-hand turn are overlaid in the figure. As the mobile home progresses through the intersection, an outer and inner envelope of points is swept out by the vehicle as it moves forward. The area enclosed by the outer and inner envelopes is referred to as a swept path and is shaped somewhat like a banana. The swept path has a maximum width at some point in the middle of the "banana" and this maximum width is commonly used to characterize and define how well different types of vehicles are able to turn. Vehicles having larger maximum swept path widths take up more room when turning and consequently are deemed less maneuverable. (The term "offtracking" is also commonly used to describe the degree of lateral movement occurring in rearward portions of a vehicle as it turns.)

The turning maneuver seen in Figure 4-1 was selected to produce a large curb clearance (between the inner envelope and the curb) by using a good portion of the entire intersection. If the vehicle was constrained (by traffic conflicts or other constraints) to utilize less of the intersection in the turning maneuver, a view like that seen in Figure 4-2 might occur instead. In Figure 4-2, the vehicle hugs the right-hand curve more closely and turns through the intersection with minimal clearance on the inside. The difference in clearances between that seen in Figure 4-1 and Figure 4-2 describes the amount of adjustment or free-play that a tractor driver has to work with when negotiating an intersection turn with a mobile home. The amount of clearance available to a driver

Figure 4-1. Low-Speed Turning and Maneuverability at Intersections: Large Curb Clearance Turn.

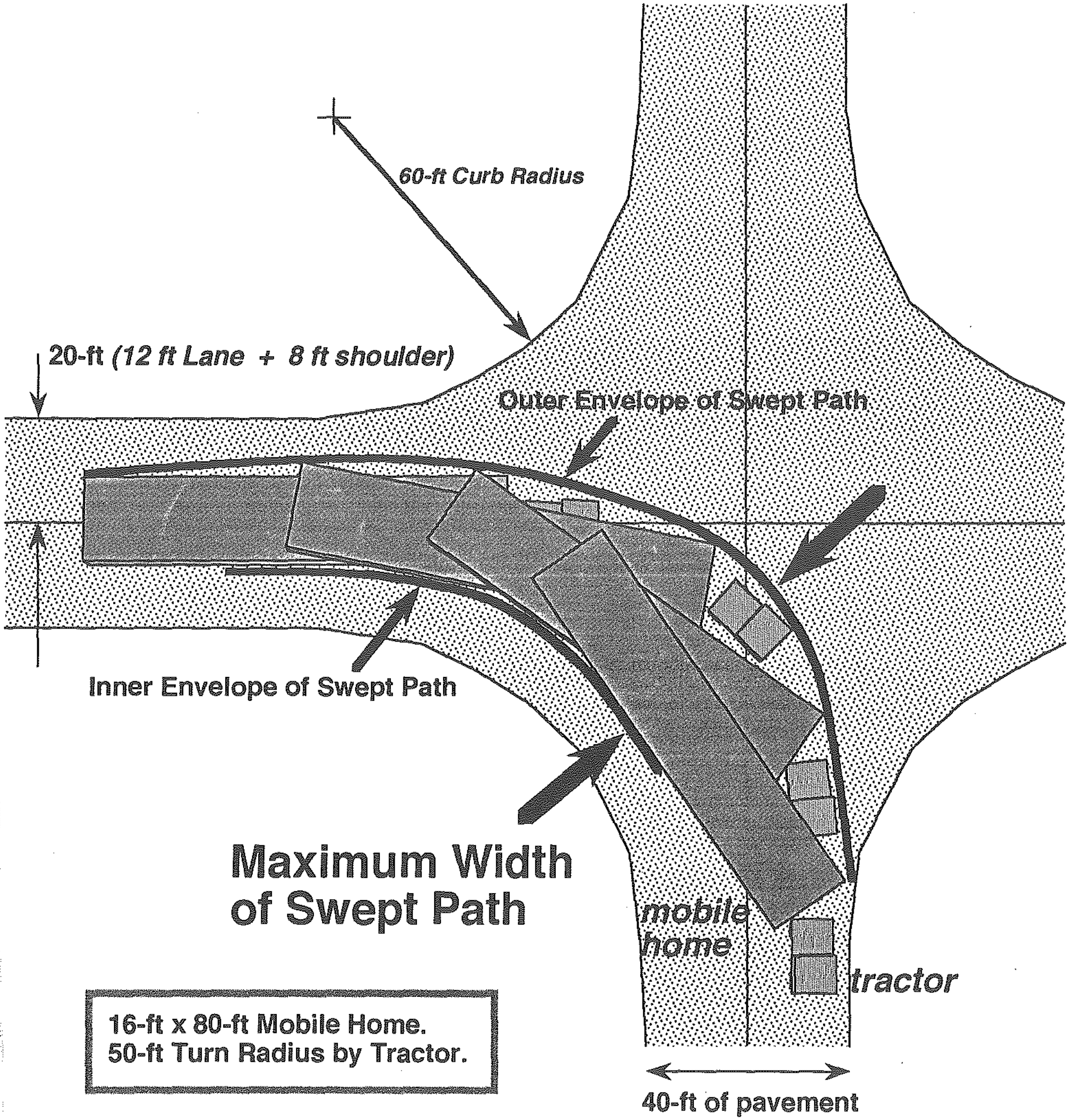
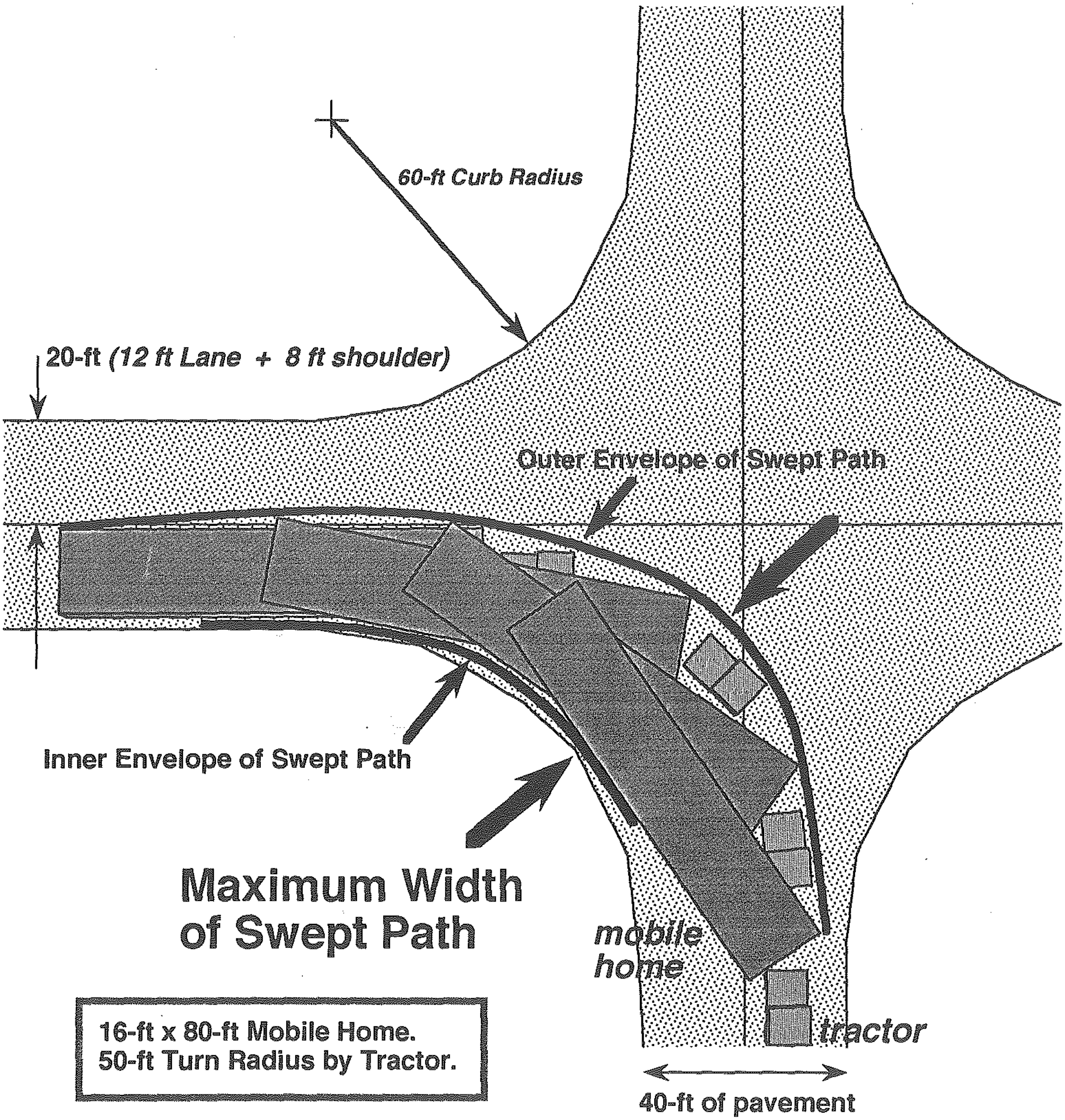


Figure 4-2. Low-Speed Turning and Maneuverability at Intersections: Minimal Curb Clearance Turn.



depends primarily upon the *geometry of the intersection*, the *path curvature of the towing tractor* through the turn, and the *geometry of the vehicle*.

The *intersection geometry* selected in this example is based approximately upon MDOT design guides for certain 2-lane, two-way, intersecting highways. In practice, the shoulder width will be somewhat tapered and different curb radii may be employed based upon the expected usage and design. If, for example, the curb radii seen in Figures 4-1 and 4-2 are reduced from 60 feet to a value of 40 feet or less, the amount of clearance available to a tractor/home combination will be reduced accordingly. If the curb radius is less than a certain threshold value, the tractor/home combination will not be able to turn cleanly through the intersection without encroaching over the curb or into adjacent roadside structures. Likewise, if shoulder width (or highway lane width) is reduced, the amount of curb clearance available to the tractor/home combination will be diminished similarly.

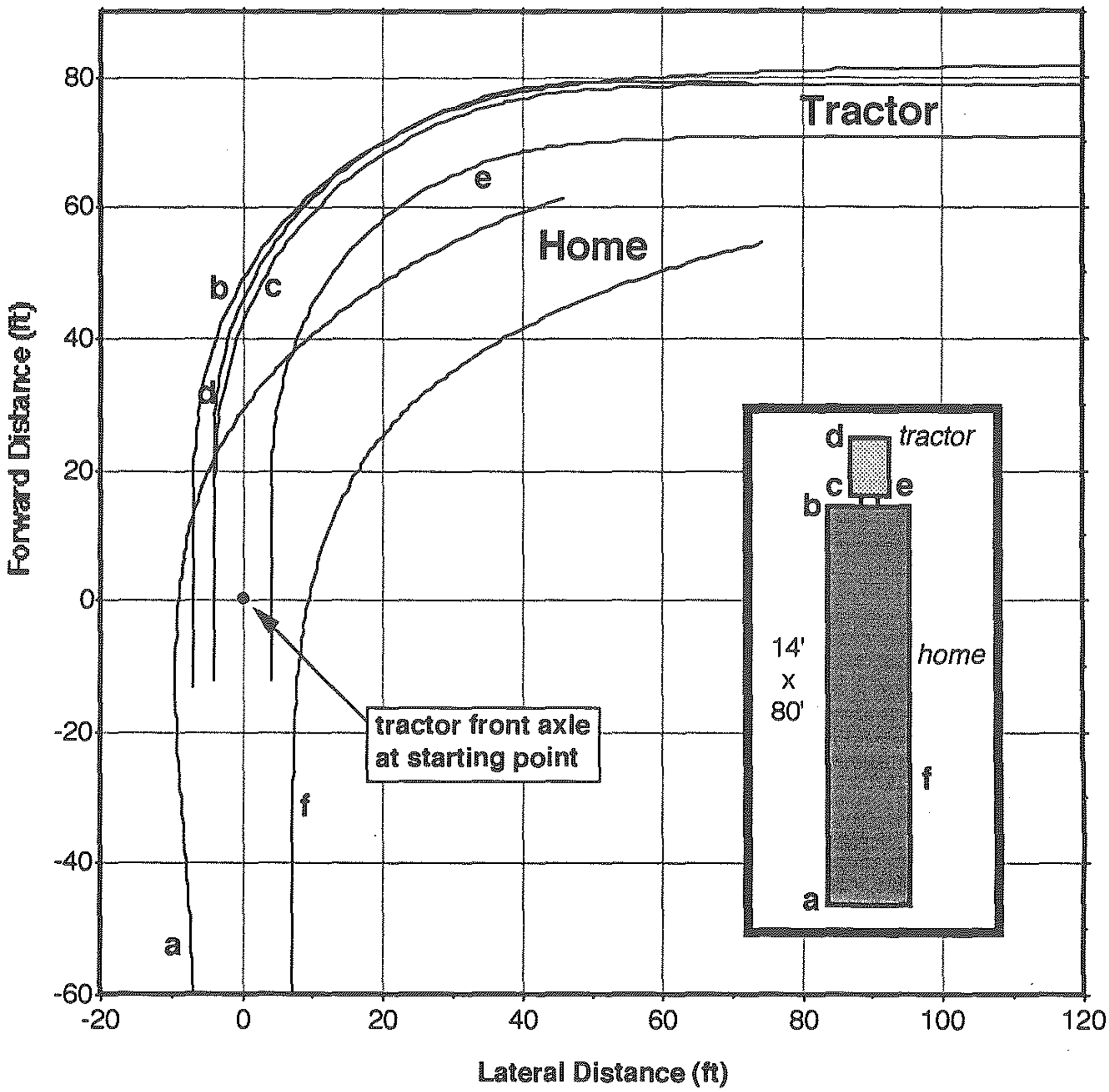
The *turning radius* of the towing tractor is assumed to be 50-ft for most of the analyses performed to date. This is based upon a set of recent low-speed turning measurements conducted by MDOT on a similar 16-ft by 80-ft home and tractor combination. Those tests indicated a minimum turning radius by the towing tractor of approximately 50 to 55-ft and were largely dictated by the nature of the hitching mechanism commonly deployed for connecting the the mobile home to the tractor unit. (Tractors normally can turn much tighter when towing conventional semitrailers.)

The *vehicle geometry* in this particular study is largely fixed except for the *width* of the home unit (14-ft, 16-ft, and 18-ft widths being examined). The length of the home is approximately 80-ft and is being towed by a tractor with a 10-ft wheelbase. It is easy to see from the diagrams in Figures 4-1 and 4-2 that if the home width is allowed to increase, the thickness of the swept path ("banana") will increase more or less in direct proportion.

To better visualize and dissect how different parts of a mobile home and tractor combination move as they progress through a turn, a somewhat more detailed diagram of the turning process is seen in Figure 4-3 corresponding to a 14-ft wide home that is 80-ft in length. In this figure, the trajectories of six distinct points (a, b, c, d, e, and f) on the combination vehicle are traced out on a grid as the vehicle moves through a right-hand turn. The maneuver is precisely the same as that seen in Figures 4-1 and 4-2. However, Figure 4-3 is less descriptive and more quantitative. In fact, the outermost portions of curves a, b, and f actually define the banana-shaped swept path described in Figures 4-1 and 4-2.

Figure 4-3. Trajectories of Various Points on a Tractor & Mobile Home Combination Vehicle as it Moves Along a 50-ft Radius Right-Hand Turn.

(14-ft Wide)



a: Outside Rear Corner of Home
b: Outside Front Corner of Home
c: Outside Rear End of Tractor
d: Outside Front Corner of Tractor
e: Inside Rear End of Tractor
f: Inside Rear Tire(s) of Home

Figure 4-4. Trajectories of Various Points on a Tractor & Mobile Home Combination Vehicle as it Moves Along a 50-ft Radius Right-Hand Turn. (16-ft Wide)

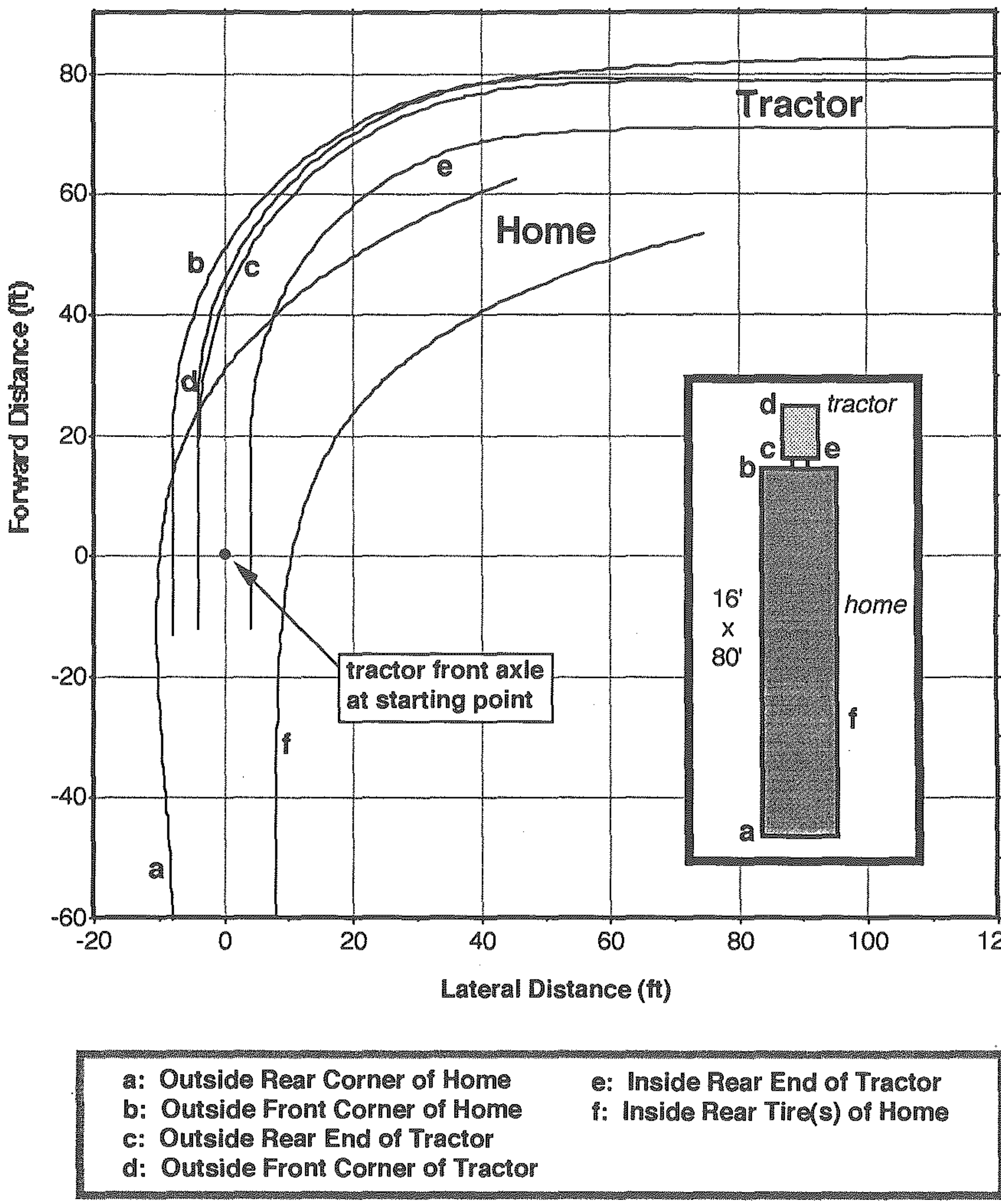
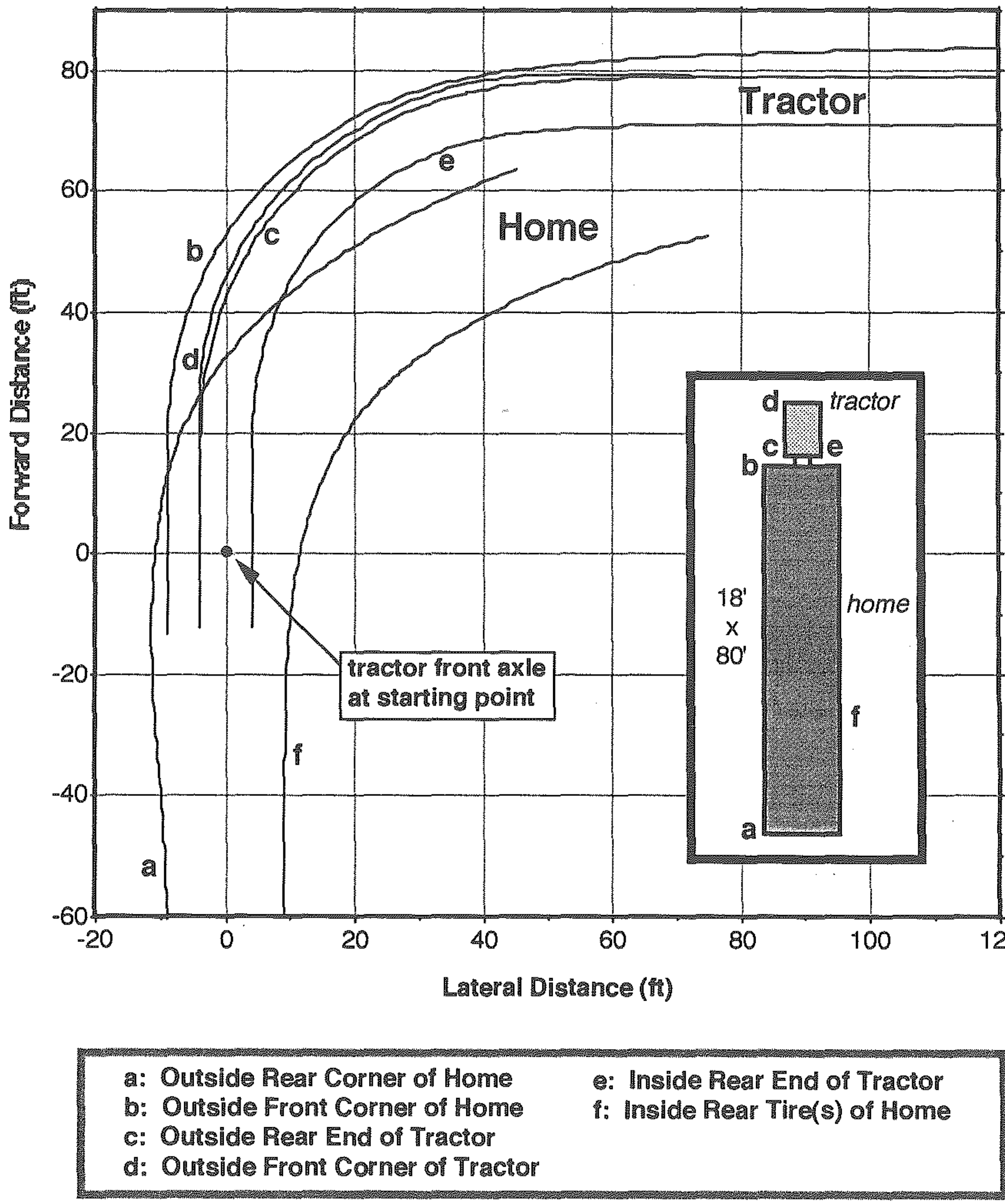


Figure 4-5. Trajectories of Various Points on a Tractor & Mobile Home Combination Vehicle as it Moves Along a 50-ft Radius Right-Hand Turn.

(18-ft Wide)



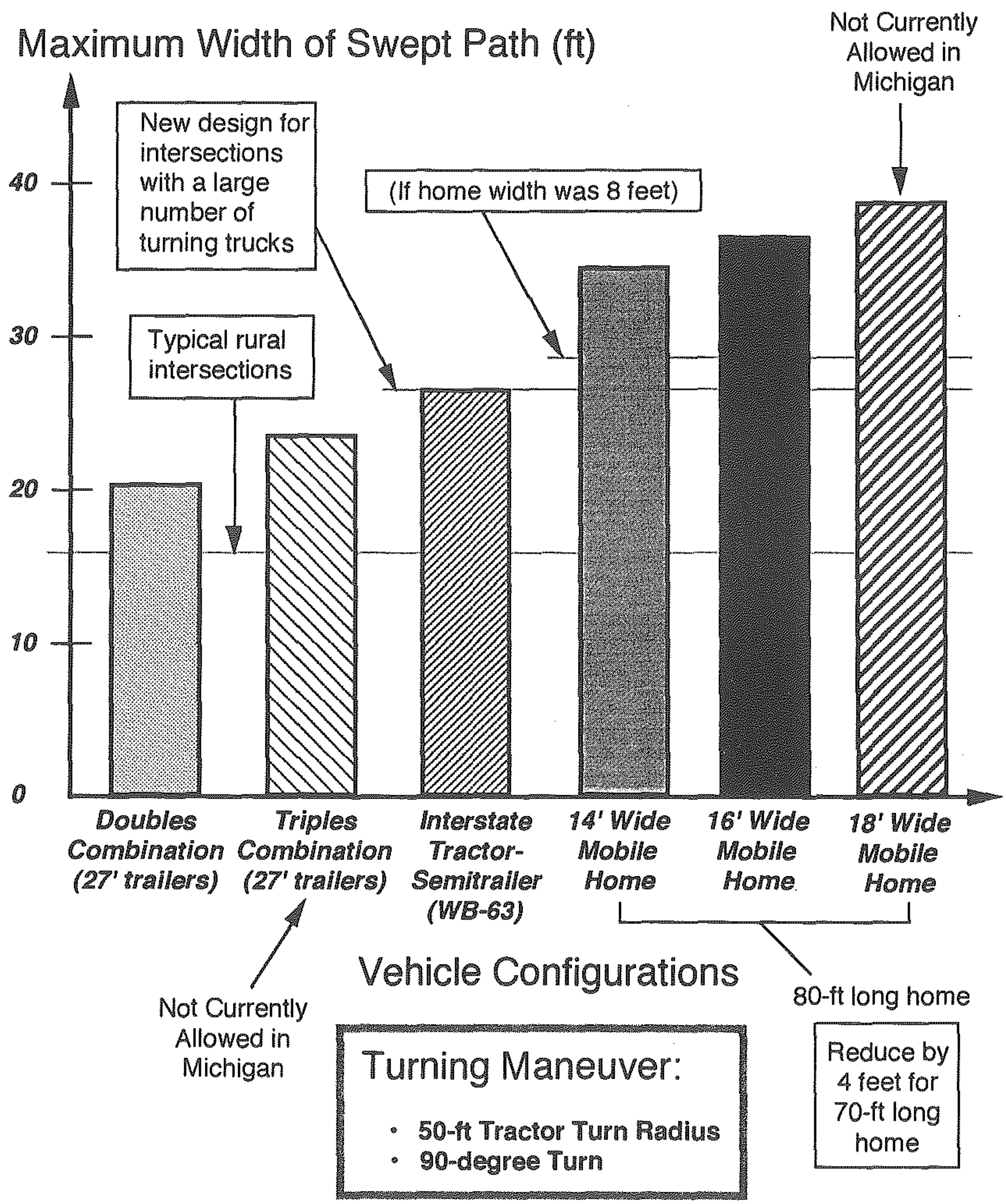
Diagrams similar to Figure 4-3, but for 16-ft wide and 18-ft wide home units, are seen in Figures 4-4 and 4-5. Each of these diagrams was used to accurately calculate the amount of offtracking, or lateral space, required by the different tractor/home combinations (14-ft, 16-ft, and 18-ft wide) when turning through an intersection.

In order to compare, in a side-by-side manner, how well other highway vehicles are able to turn and maneuver through an intersection relative to mobile homes, a sequence of calculations was conducted for several large highway vehicles. These included a 70-ft long double combination vehicle, a 105-ft long triple combination vehicle, and a long interstate tractor-semitrailer with an overall length of 70 feet. Each of these vehicles was steered through the same turn (as seen in Figures 4-1 to 4-3) used for the mobile home. The maximum widths of the swept paths were then tabulated. The results are seen in Figure 4-6 where each of the large highway vehicles are compared with identical calculations for three mobile home / tractor combinations of various widths (14-ft, 16-ft, and 18-ft widths). Two of the vehicle combinations seen on this chart (the triple trailer combination and the 18-ft wide mobile home) are not currently permitted to operate in the state of Michigan but are included here for comparison. As seen, each of the mobile homes does exhibit considerably larger swept path widths when compared with the three highway vehicles — exceeding the largest of these (the long interstate tractor-semitrailer) by 9 feet or more.

One primary reason for the large swept path widths exhibited by the mobile home is its length — 80 feet. The other contributing factor seen here is width. If the width of the mobile homes was the same as most other large highway vehicles (8 feet), the maximum width values seen in Figure 4-6 would be reduced to values of about 28.5 feet on the maximum swept path width chart. If one were to assign a percentage contribution to length and width as factors associated with swept path width for the example intersection seen above, mobile home length would contribute about 56% and mobile home width about 44%. Consequently, width is an important ingredient in the overall picture of how well mobile homes (and other highway vehicles) are able to turn and maneuver through actual intersections encountered on the highway system.

The issue of how much additional swept path width is required by mobile homes if permitted home widths increase from 14 feet to 16 feet (or possibly 18 feet) is illustrated in Figure 4-6 by the three mobile home bars. The additional width requirement in swept path (beyond that currently utilized by a 14-ft wide home) will be 2 feet for a 16-ft mobile home and 4 feet for an 18-ft wide mobile home. If the length of the home units is reduced to 70-ft, the bars on this chart for each the mobile homes would be reduced by about 4 feet.

Figure 4-6. Comparison of Maximum Swept Path Widths for Various Types of Highway Vehicles.



Another factor that has not been discussed, but is particularly important for mobile homes, is the overhang or swing-out behavior exhibited by the outside rear-end of such vehicles during tight turning at intersections. This occurs primarily because the forward location of the axles on the mobile home is at a point slightly rearward of the mid-point of the home. It was noted above that the minimum turning radius of the towing tractor is observed to be about 50 feet based upon recent MDOT tests. For that degree of turning curvature, the outside rear end of an 80-ft long mobile home swings out about 2 feet towards the left-hand lane (from its initial straight-line direction at the beginning of the turn). See, for example, Figure 4-2 or 4-3. If, however, the tractor was capable of turning on a tighter circular path, for example a 25-ft radius, the swing-out effect at the rear end of the mobile home would increase considerably to about 6 feet. Consequently, offtracking advantages accruing from being able to turn more sharply with the towing tractor are to some extent offset by the pronounced development of swing-out behavior of the outside rear end of the home unit. (For most highway vehicles this swing-out behavior is extremely small due to the more rearward position of the axles on such vehicles.)

For oncoming traffic on a two-lane highway that encounters a 16-ft wide home (instead of a 14-ft wide home) at an intersection, the amount of encroachment by the rear end of the home unit (towards the oncoming traffic) will be the amount of swing-out that occurs with a 14-ft wide home *plus* an additional 1 foot (half the difference in home widths). This of course assumes that the towing tractor follows the same turning path through the intersection for both homes. Consequently, the net effect for oncoming traffic is an additional encroachment amount that is equal to half the difference in home widths, beyond that already produced by the rear end swing-out behavior.

Curb Clearances at Intersections

The above discussion and results have described findings related to how much lateral space is <u>required</u> by a tractor/home combination when turning through an unrestricted 90-degree or right-hand turn. However, the amount of <u>available</u> space is the other important factor in any such analysis, since it is the difference between available space and required space that introduces potential conflicts for tractor/home combinations and other highway users.

The amount of available space is of course determined by the geometry of the highway intersection. This geometry is primarily described by paved surface widths (or throat widths) at the entrance and exits of intersections, as well as the curb radius used to connect the entrance and exit road segments.

Certain assumptions are used here in order to fairly compare curb clearance requirements for homes of different widths. The first assumption is that each tractor/home combination is compared against each other using identical intersection geometries and that these intersection geometries are reasonable and representative of those encountered in Michigan. The second assumption is that the same geometric constraints be placed upon each tractor/home combination as it starts the turn, moves through the turn, and exits the turn.

With this in mind, turning analyses were conducted for three different intersection geometries to evaluate the available curb clearances with mobile homes of three different widths. Curb radii were varied from 30 feet (typical design for many existing intersections) up to 70 feet (current design practice) and home widths were varied from 14-ft to 16-ft to 18-ft. The path taken by the tractor/home vehicle when turning through each intersection was assumed to start from an approximate left-lane location upon entrance to the intersection, and utilized the full pavement width available upon exit from the intersection. See Figure 4-7.

Obviously, different initial offsets, d, as described in Figure 4-8, affect the amount of clearance available to a vehicle as it turns through a particular intersection. For purposes of these analyses, reasonable initial offsets were selected that placed the left side of the home unit (a) on the centerline (d0 = 0), (b) two feet to the left of the centerline (d0 = +2), and (c) two feet to the right of the centerline (d0 = -2). (*Note that as discussed in the previous section, swing-out encroachments into the oncoming lane by the rear end of the home unit — midway through the turn — will exceed these initial offset values by approximately 2 feet. Consequently, only the d0 = -2 ft case produces no encroachment by the home unit into the oncoming lane. Offsets of d0 = 0 and d0 = +2 produce encroachments by the rear end of the home unit of 2 feet and 4 feet, respectively.*) It was also assumed that the tractor towing unit always followed a 50-ft radius turn. The resulting curb clearances that were calculated in the analyses illustrate the extent to which home width influences the amount of available curb clearance for the described set of conditions.

To help select example intersections to use in the curb clearance analyses, MDOT provided two representative intersection geometries for Michigan highways. These are seen in Figures 4-9 and 4-10. Figure 4-9 represents a state trunkline to county road intersection example with curb radii potentially varying in the range of 30-ft to 70-ft, depending upon the particular intersection. The state trunkline contains 2 sets of 12-ft lanes separated by a median strip or 12-ft-wide left-turning center lane. The county road contains four 12-ft lanes (or two 12-ft lanes and two 12 ft-wide shoulders).

Figure 4-7. Basic Turning Maneuver and Curb Clearances at an Intersection.

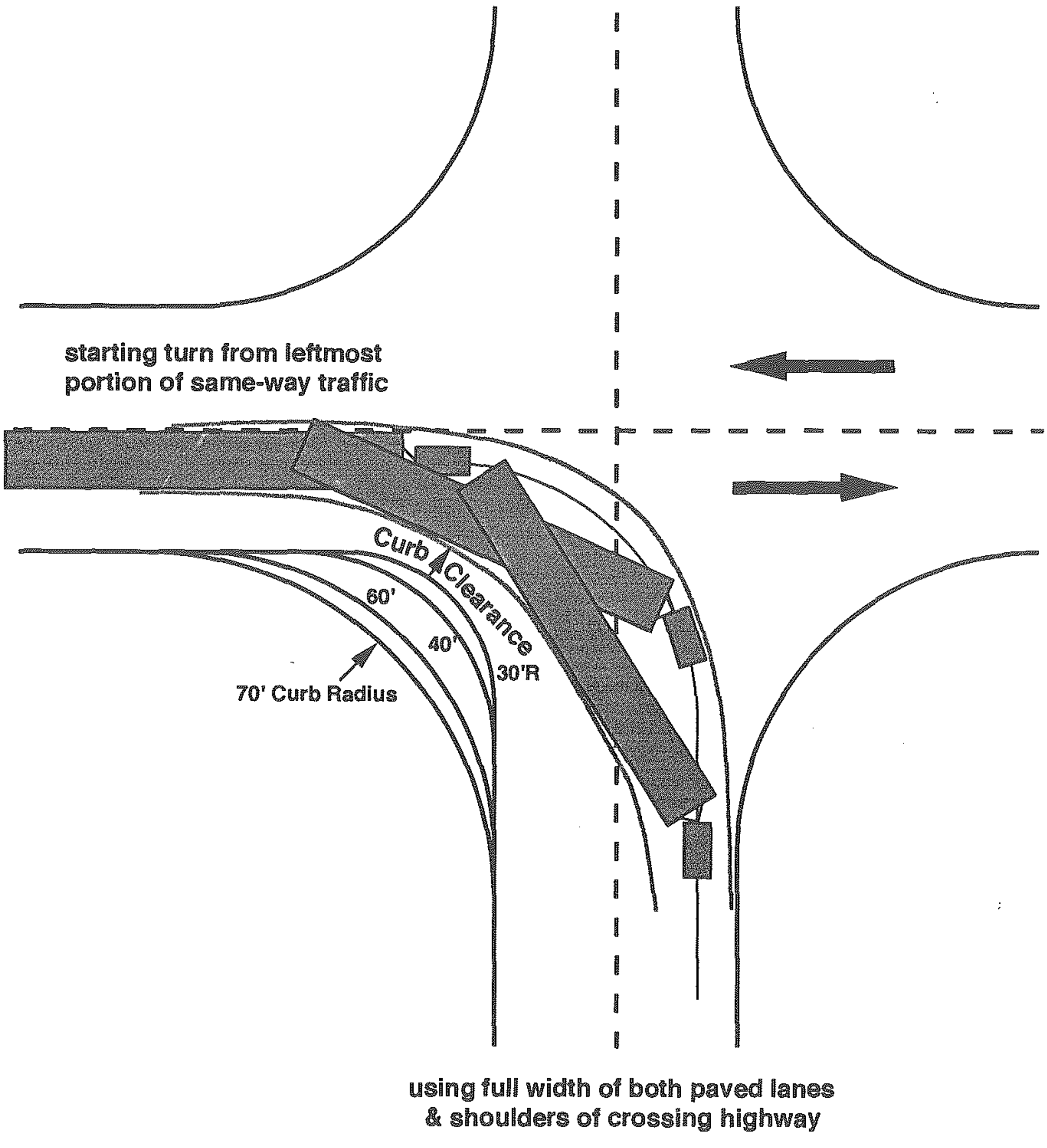


Figure 4-8. Effect of Different Initial Offsets on Avaialble Curb Clearance.

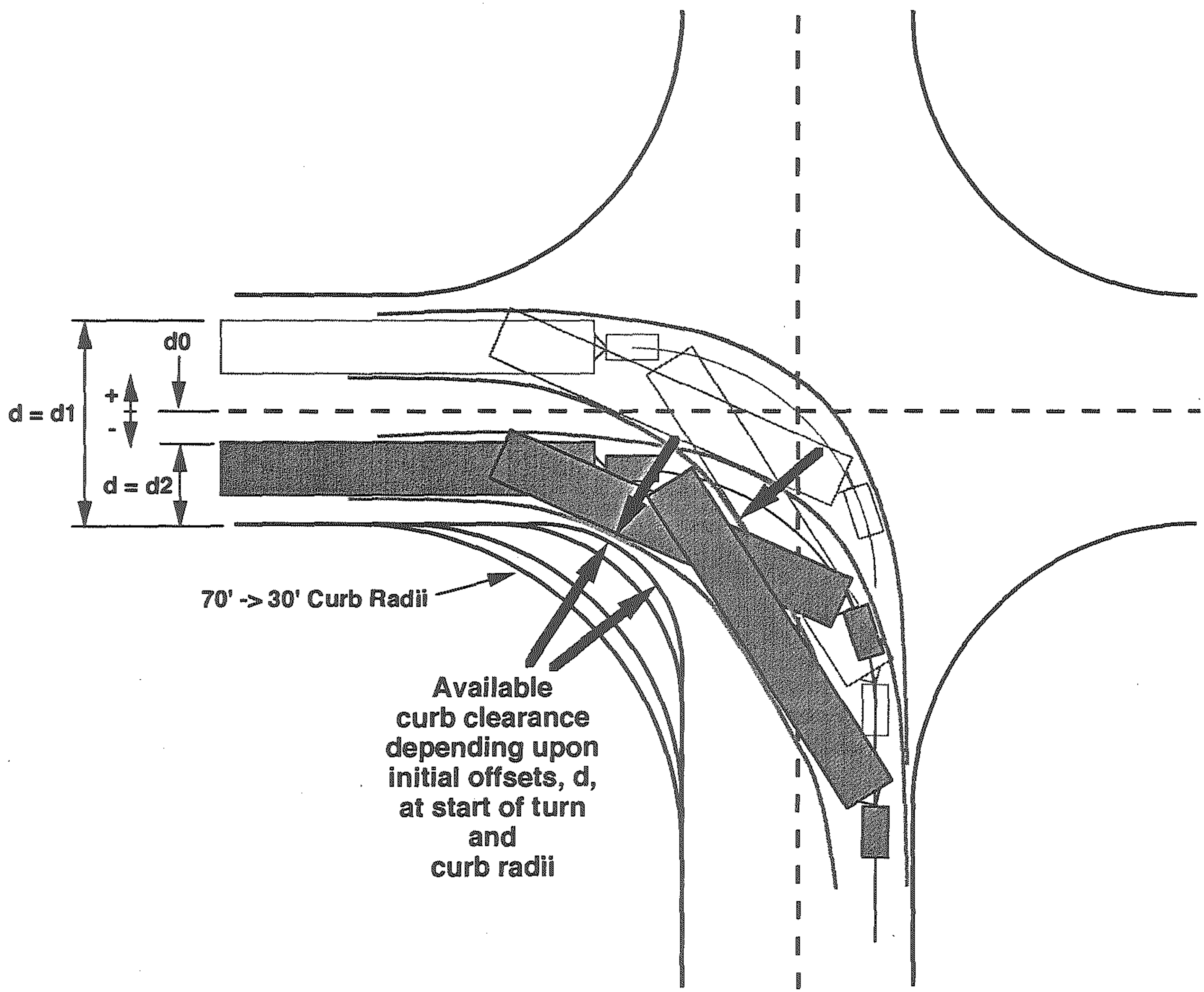


Figure 4-9. State Trunkline to County Road Intersection.

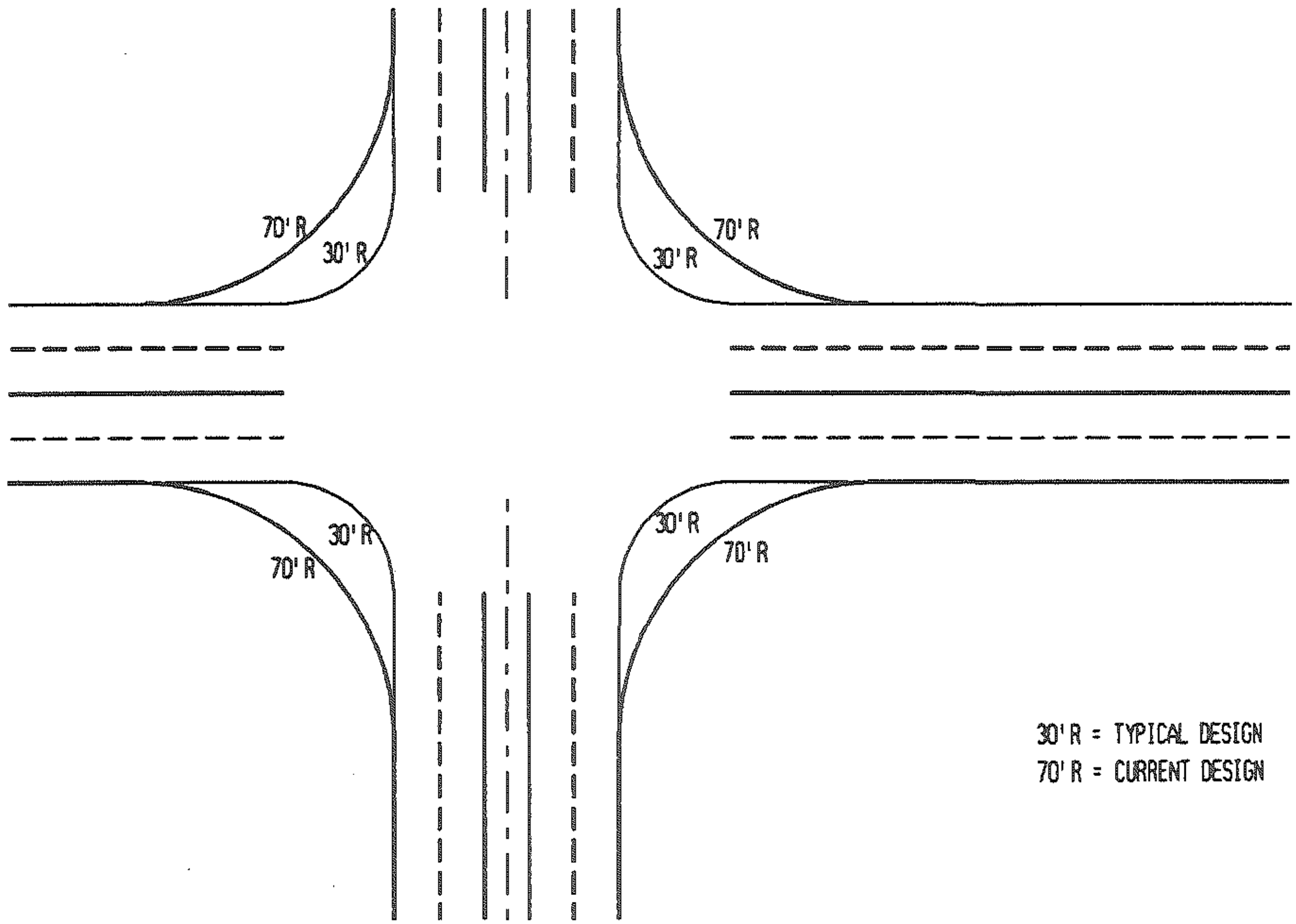
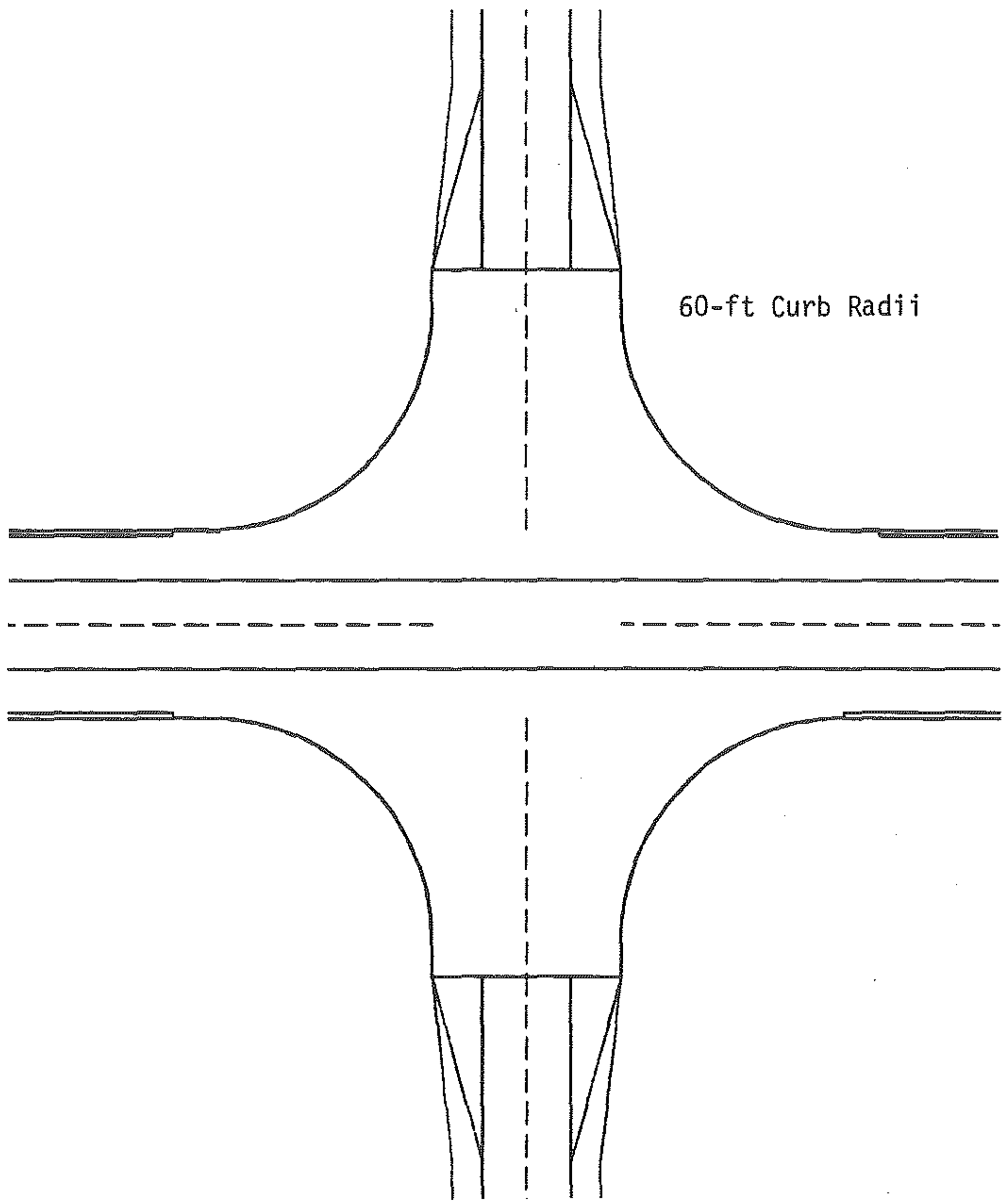


Figure 4-10. Rural Road Intersection.



In Figure 4-10, an alternate rural road intersection is seen having a 60-ft curb radius. The primary road in this example contains 12-ft wide lanes and 12-ft wide shoulders. The secondary cross-road (tapered shoulders at throat) contain two 12-ft lanes and 8-ft shoulders.

The basic features of these two example cases were combined into three separate intersection types differing from one another only by their respective entrance and exit widths. These three intersection types are defined in Figure 4-11 and are the intersection geometries upon which the curb clearance calculations were based. As seen in Figure 4-11, "Intersection Type 1" provides entrance and exit pavement widths of 48-ft. The curb radii vary from 30-ft to 70-ft. "Intersection Type 2" has an entrance pavement width of 48-ft and an exit pavement width of 40-ft. Curb radii likewise vary from 30-ft to 70-ft. Lastly, "Intersection Type 3" is described by entrance and exit pavement widths of only 40-ft, also with curb radii varying in the range of 30-ft to 70-ft.

Utilizing these three intersection geometries, curb clearance calculations were conducted for each of the three home widths and for three different initial offset values. The initial offset values, as described earlier, correspond to the left home edge (a) on the centerline (d0 = 0), (b) 2 feet to the left of centerline (d0 = +2), and (c) 2 feet to the right of centerline (d0 = -2). The turning direction through the intersection is to the right in all cases. The home lengths are all 80 feet.

The results of these calculations appear in Figures 4-12 to 4-14. Each figure corresponds to the intersection type (1, 2, or 3). Each graph shows curb clearance plotted versus curb radius and corresponds to a home width of either 14-ft, 16-ft, or 18-ft. The three lines on each graph correspond to initial offset values of +2, 0, or -2 feet from the centerline (left side of home unit).

Intersection Type 1 — 48-ft wide entrance / 48-ft wide exit)

For Figure 4-12 (Intersection Type 1), the results indicate that 14-ft wide mobile homes (bottom graph) are able to turn through this intersection for any curb radius in the range of 30-ft to 70-ft without encroaching into oncoming traffic. Since many existing Michigan intersections contain 30-ft curb radii, the 14-ft wide home will not encounter curb clearance conflicts for most curb radii used with this type of intersection.

For the 16-ft wide home (center graph), curb clearance conflicts begin to be observed for this same intersection geometry and curb radii of 30-ft (d0 = -2 case specifically). However, the 16-ft wide home is able to turn through the "type 1 intersection" without conflict for curb radii greater than 30-ft. (i.e., almost all cases).

Figure 4-11. Definition of Three Intersection Geometries Examined for Curb Clearances.

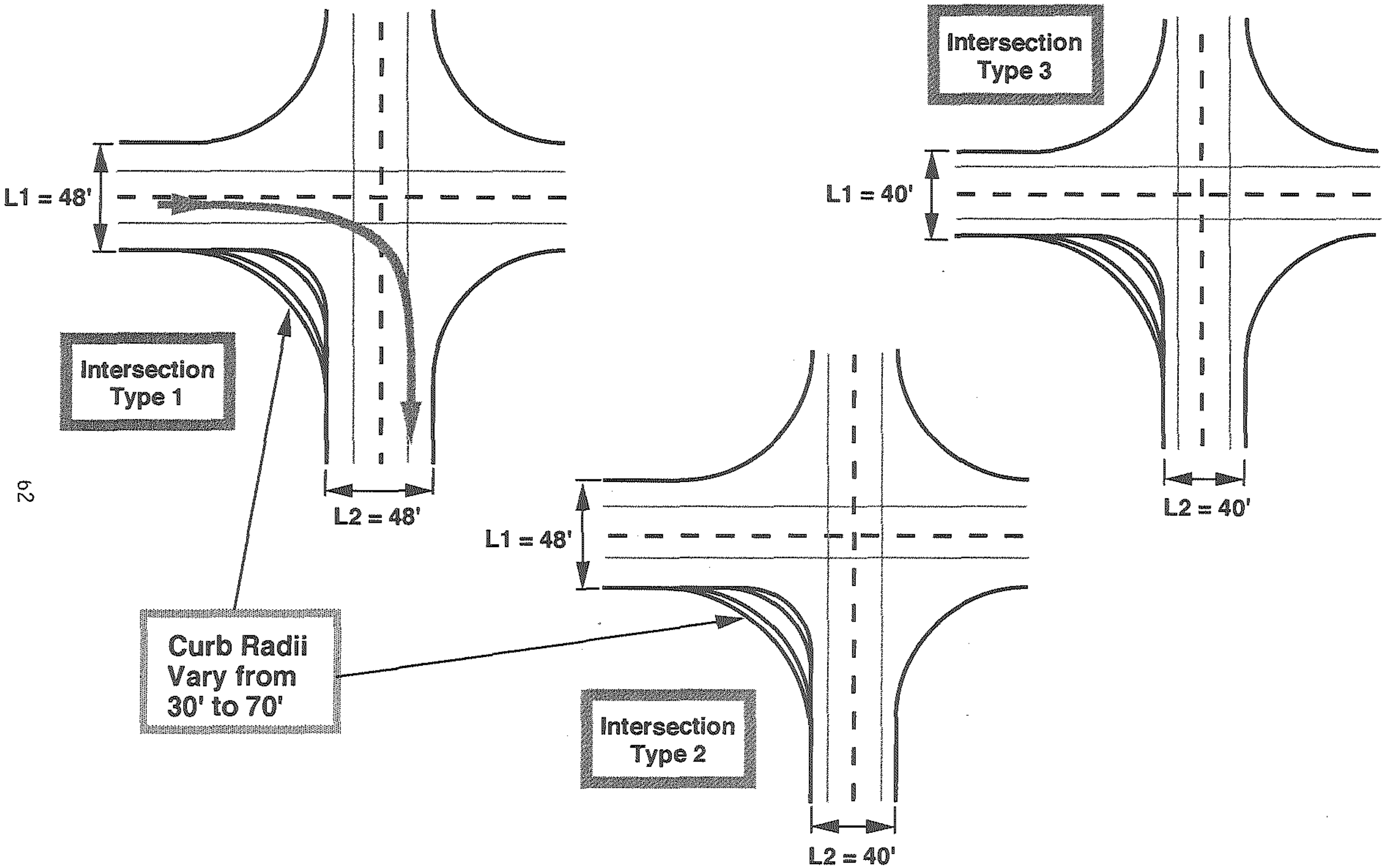


Figure 4-12. Curb Clearance vs. Curb Radius. Intersection Type 1. Three Home Widths & Three Initial Centerline Offsets (d0).

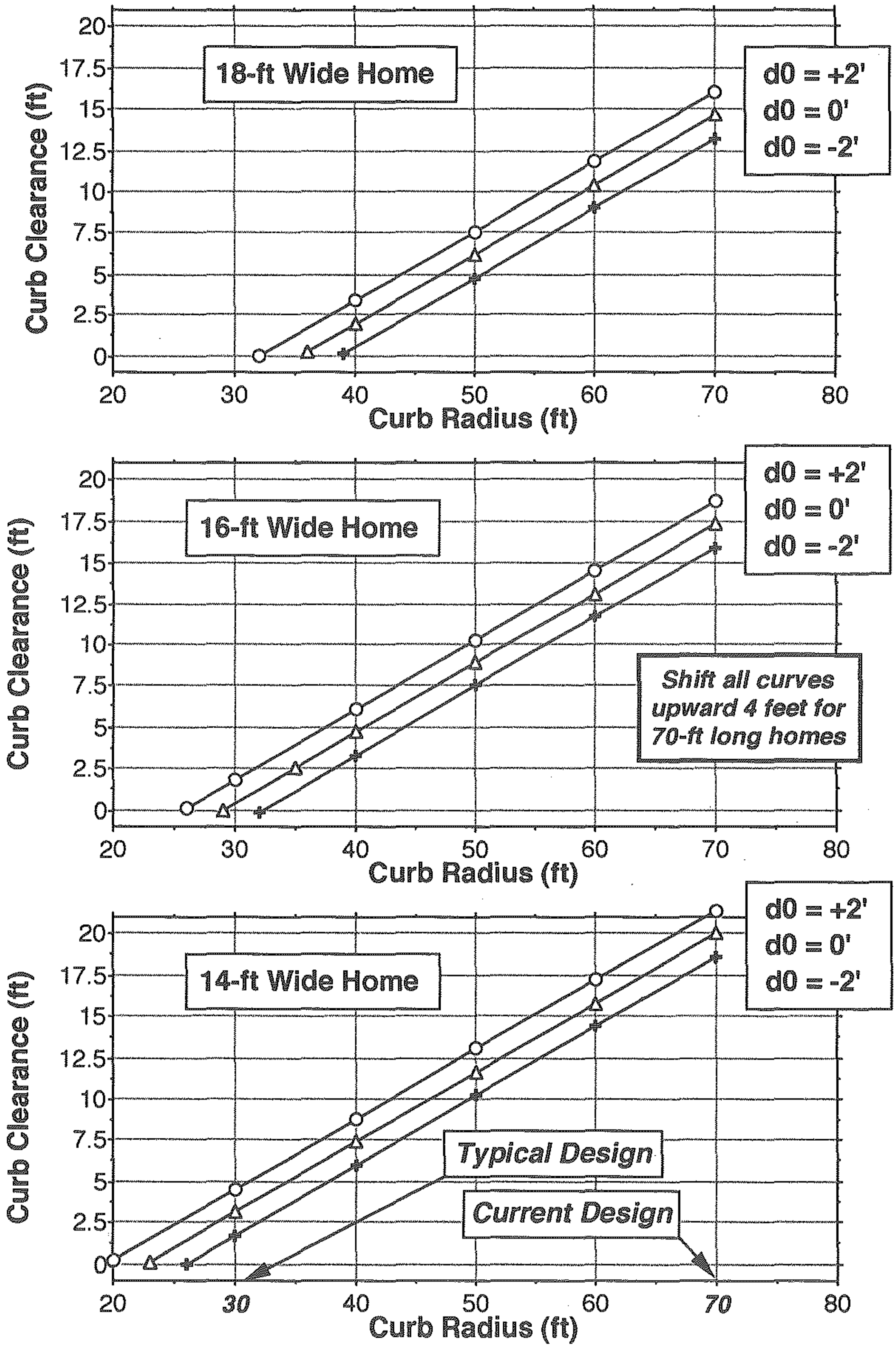
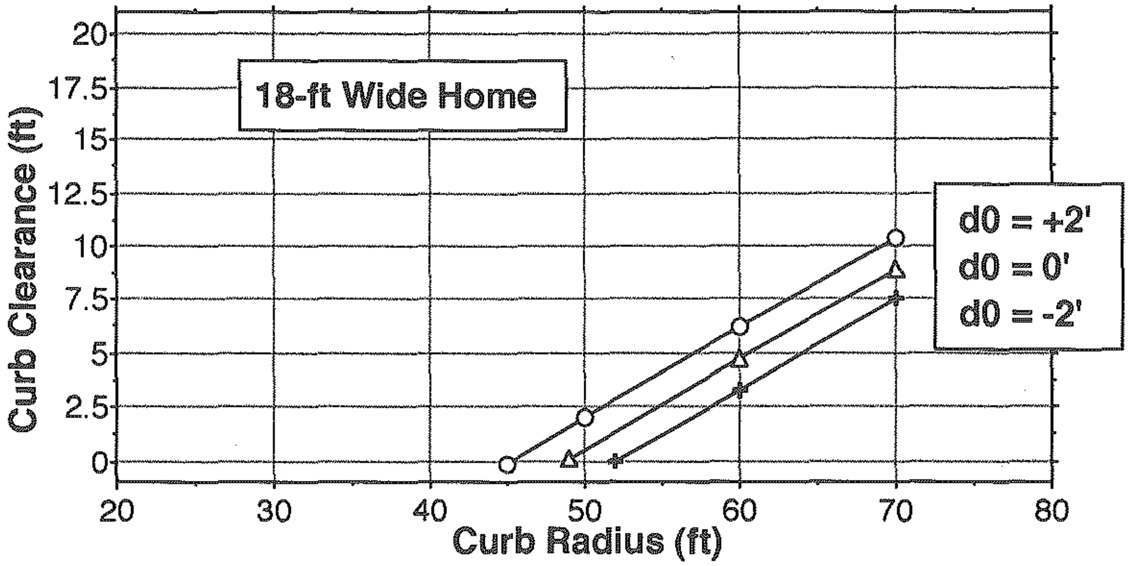
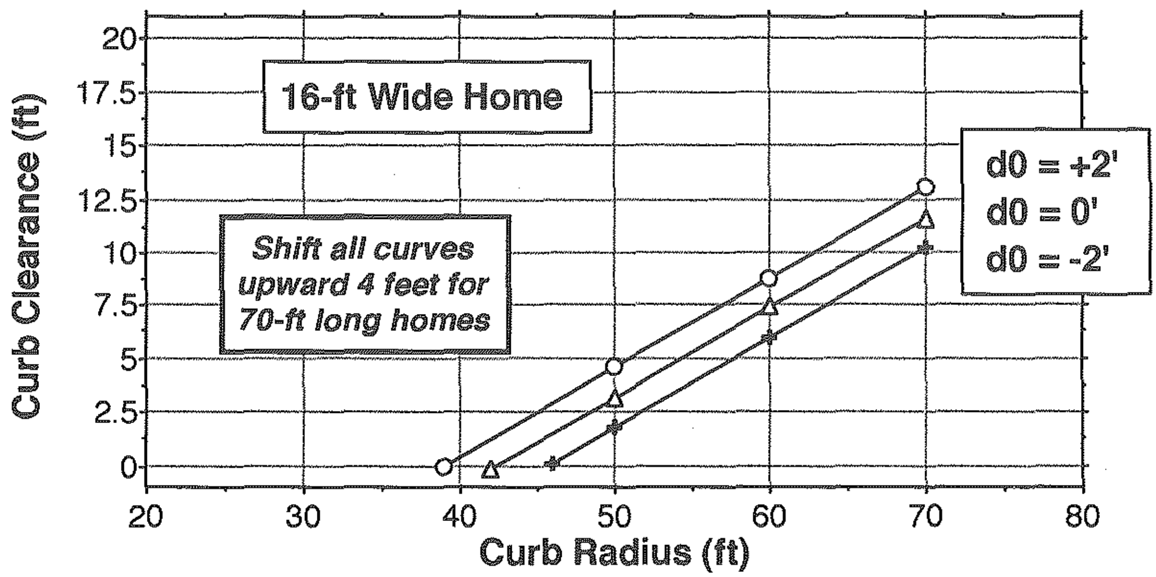


Figure 4-13. Curb Clearance vs. Curb Radius. Intersection Type 2. Three Home Widths & Three Initial Centerline Offsets (d0).





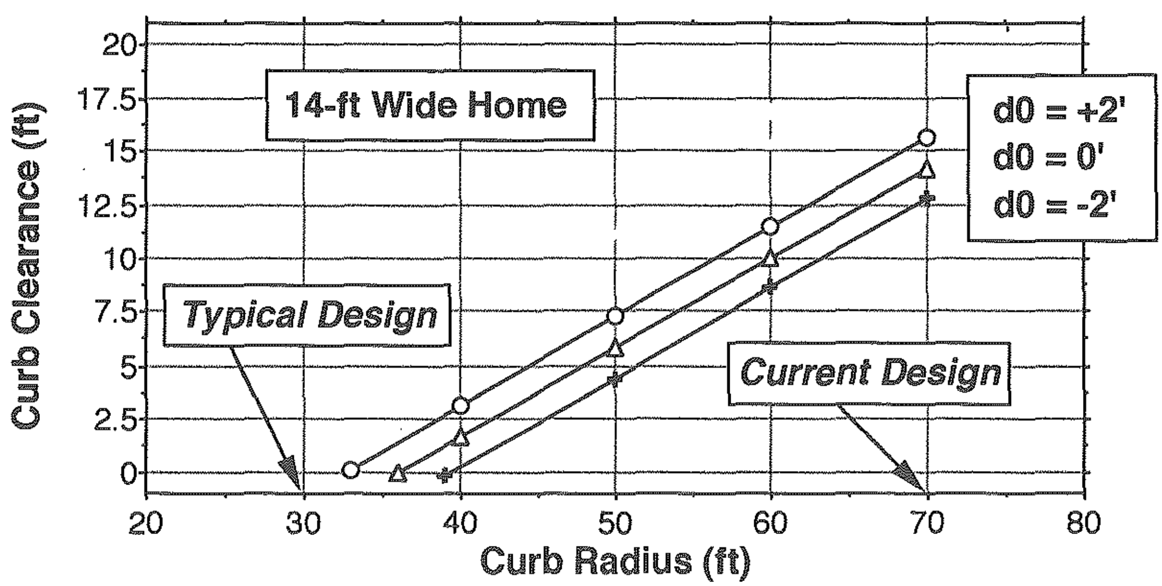
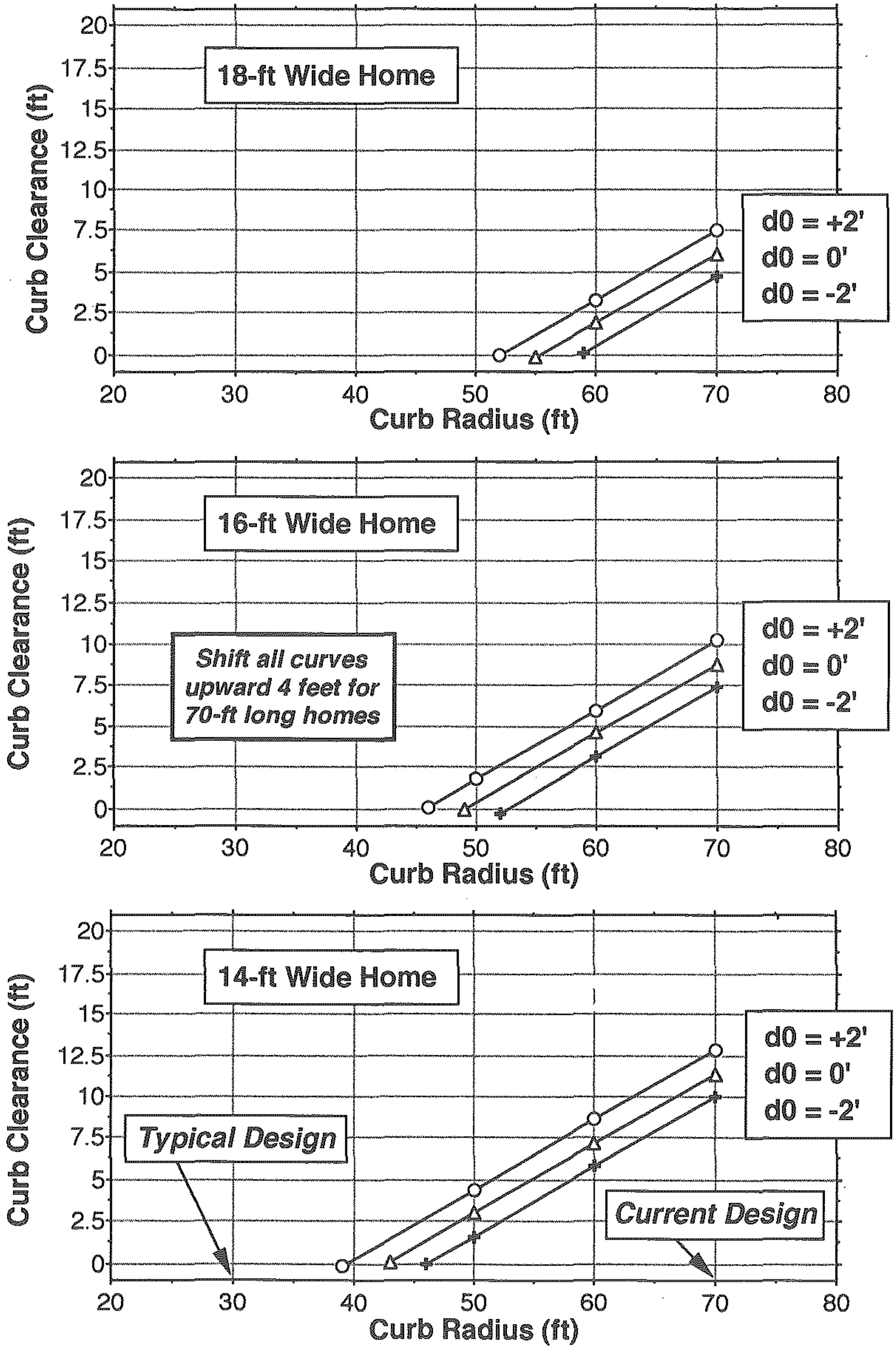


Figure 4-14. Curb Clearance vs. Curb Radius. Intersection Type 3. Three Home Widths & Three Initial Centerline Offsets (d0).



In the case of the 18-ft wide home (top graph) and the type 1 intersection, curb clearance conflicts are apparent for curb radii less than 39-ft. Consequently, those existing intersections in Michigan having 30-ft radii do not provide sufficient room for 18-ft wide homes unless large initial offset encroachments into oncoming traffic (3 feet or more) are used by the towing tractor.

Intersection Type 2 — (48-ft wide entrance / 40-ft wide exit)

Turning now to Figure 4-13 and the "type 2 intersection," 14-ft wide homes (bottom graph) are free of curb clearance conflicts provided the curb radius is greater than 35 feet (using the d0 = 0 line). Consequently, those existing intersections having 30-ft radius curbs would require significant initial offset encroachments (4 feet or so) by the 14-ft wide home into oncoming traffic in order to cleanly turn through a type 2 intersection.

The results for the 16-ft wide home in Figure 4-13 (center graph) are even more restrictive indicating a minimum curb radius of approximately 42 feet. Thus, 16-ft wide homes would require an additional 7 feet of curb radius (increased from 35 to 42 ft) for this intersection in order to achieve clearances comparable to those of 14-ft wide homes. (This of course assumes that the home unit is restricted from any initial offset encroachment into oncoming traffic lanes, or, d0 = 0.)

The 18-ft wide home (top graph) requires yet another 7 feet of increased curb radius (to 49-ft) for this same intersection in order to avoid curb-side clearance problems.

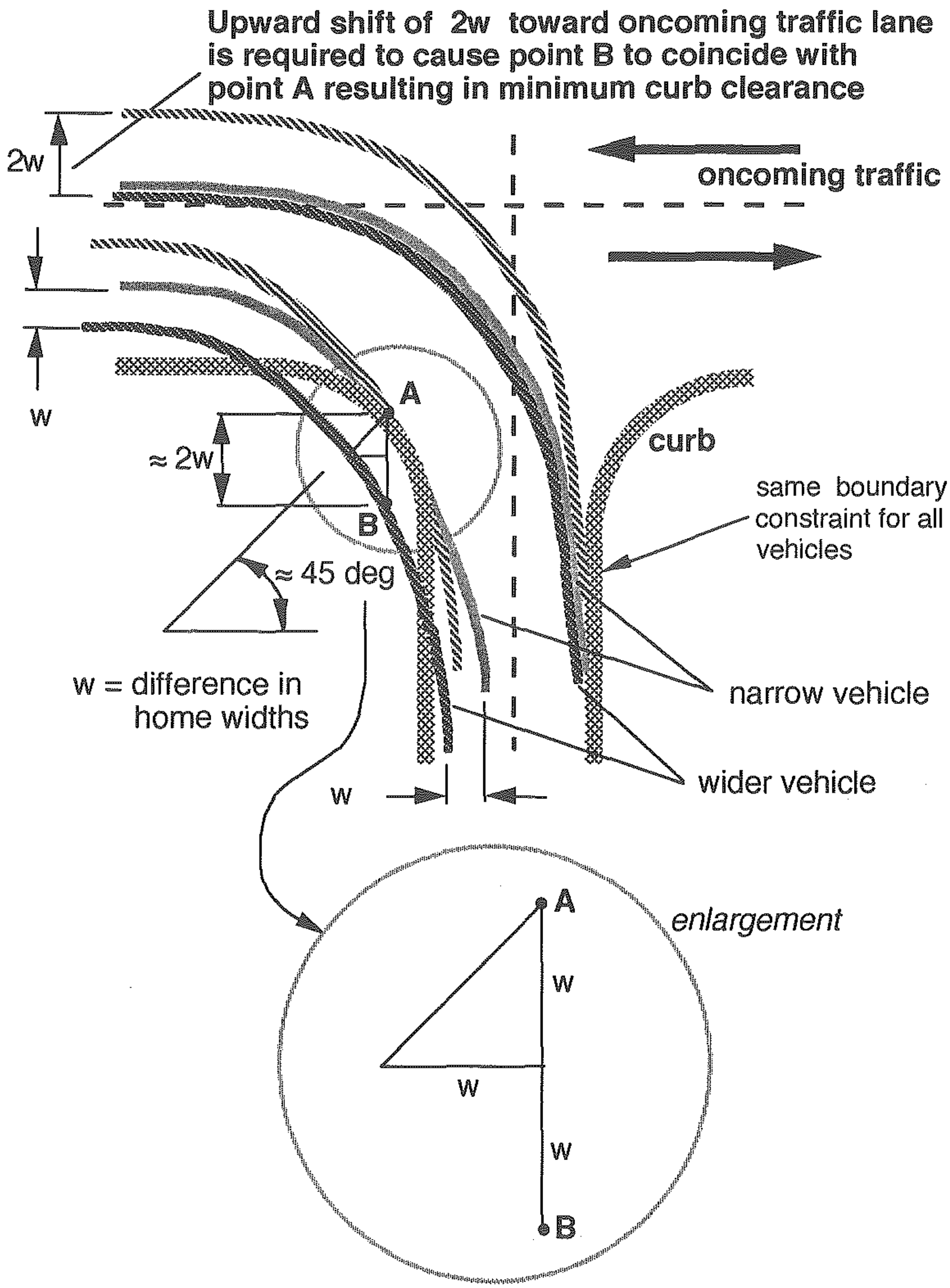
Intersection Type 3 — (40-ft wide entrance / 40-ft wide exit)

Lastly, Figure 4-14 shows corresponding results for the the most restrictive of the three intersection types, the "type 3 intersection" with 40-ft wide paved entrance and exit widths. The minimum curb radii for the three home widths (14-ft, 16-ft, and 18-ft) are seen to be: 43-ft, 49-ft, and 55-ft, respectively. Consequently, if a 14-ft wide home encounters a type 3 intersection with 30-ft curb radii, an initial offset into oncoming traffic of approximately 7 feet would be required order to avoid curb conflicts. This would leave oncoming traffic 5 feet of lane width and 8 feet of paved shoulder width to pass the encroaching home in the opposite direction. Similarly, 16-ft and 18-ft wide homes would require initial offset encroachments into oncoming traffic of roughly 11 feet and 15 feet respectively. In the case of the 16-ft wide home, all oncoming vehicles would be forced entirely onto their shoulder. The 18-ft wide home would block all but the narrowest of oncoming vehicles from getting through this intersection. Clearly, none of these three turning scenarios is desirable because of the severe encroachment requirements by the homes into oncoming traffic to avoid curb-side conflicts.

For intersection types such as these that do impose specific constraints on turning vehicles, an additional foot or two of home width actually translates into twice as much required turning space in order to turn cleanly through the intersection. For example, the 7-ft offset requirement of the 14-ft wide home is magnified into an 11-ft offset requirement (4 additional feet) when the home width increases by 2 feet (to a 16-ft width). Likewise, the lateral initial offset requirement for the 18-ft wide home increases by 8 feet (from 7 to 15) even though the home width increases only 4 feet (14 to 18) — a doubling effect. Consequently, when realistic intersection geometries and clearance constraints are imposed on the turning tractor/home combination, home units of increased width actually require twice as much additional intersection space as the increase in home width itself. Furthermore, all of this additional space is taken up in the form of lateral encroachments towards, or into, the oncoming traffic lanes. In other words, if a tractor/home unit is presently able to just barely turn through a given intersection with minimal clearance, a similar tractor/home unit that is 2 feet wider would require an additional 4 feet of leftward offset (towards or into oncoming traffic lanes) in order to turn through the same intersection with minimal clearance. This magnification of required space deriving from increased home width is significant, particularly since all of the additional space required by the tractor/home combination is obtained by offsetting the tractor/home combination towards oncoming traffic lanes.

The simple diagram in Figure 4-15 helps to illustrate this point by comparing how two swept path shapes (or "bananas" as described earlier) of different widths interact with the curb when considering the same turning maneuver. If point A on the diagram represents the point of minimum clearance for the narrower vehicle, point B represents a similar point on the wider vehicle swept path. In order for the wider vehicle to turn cleanly through the indicated turn with minimum clearance (i.e., causing point B to be shifted upward to coincide with point A, thereby avoiding any curb-side conflict), the wider vehicle swept path profile (or "banana") must be shifted upward on the diagram by an amount 2w, or, twice the difference in home widths. The simplified illustration assumes that the critical point of conflict (point A) is approximately 45 degrees through the turn. Likewise, it is assumed that both vehicles are using the full width of the exit throat and that only upward shifting (toward the oncoming traffic) of the swept path area is an option for achieving the desired clearance at point A.

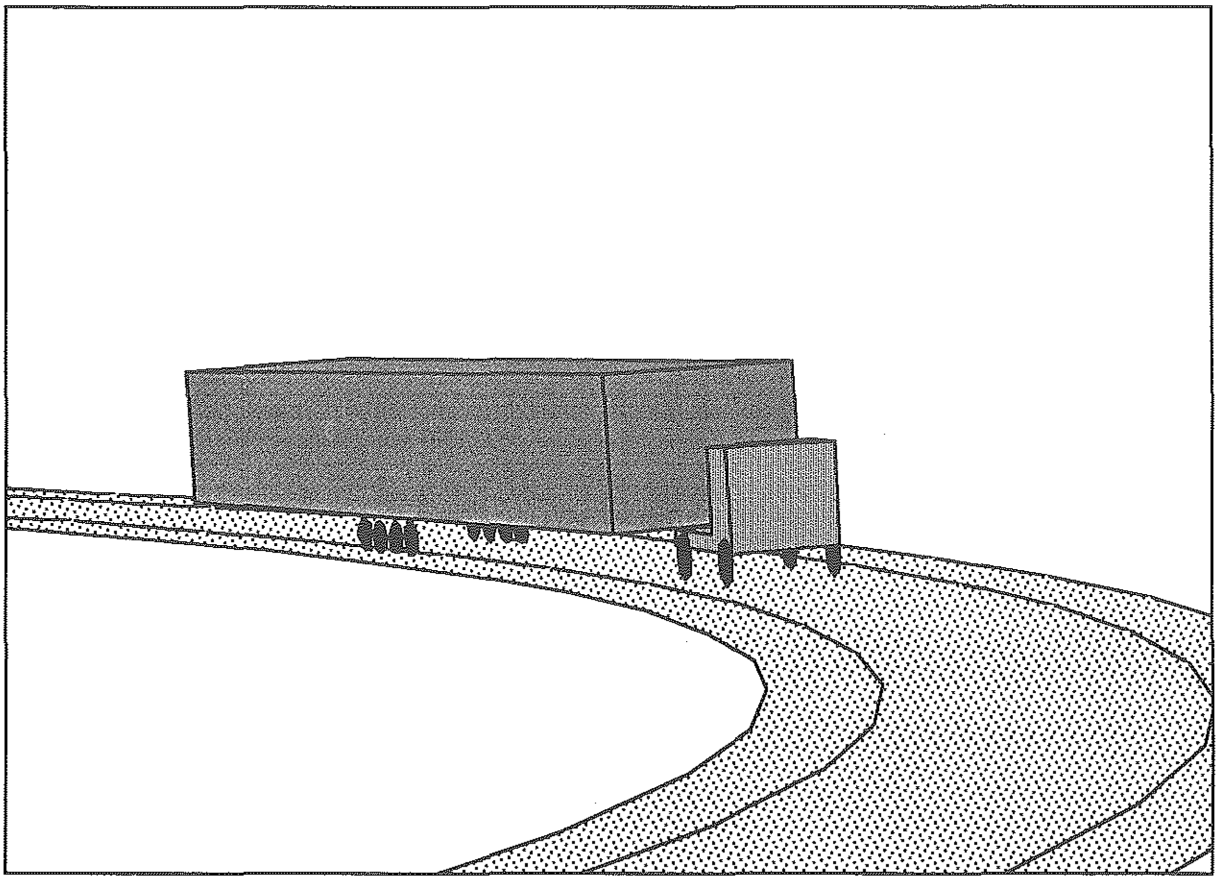
Figure 4-15. Magnified Encroachment Requirements at Intersections Due to Increased Home Width.



Low Speed Turning Along a Freeway Exit Ramp

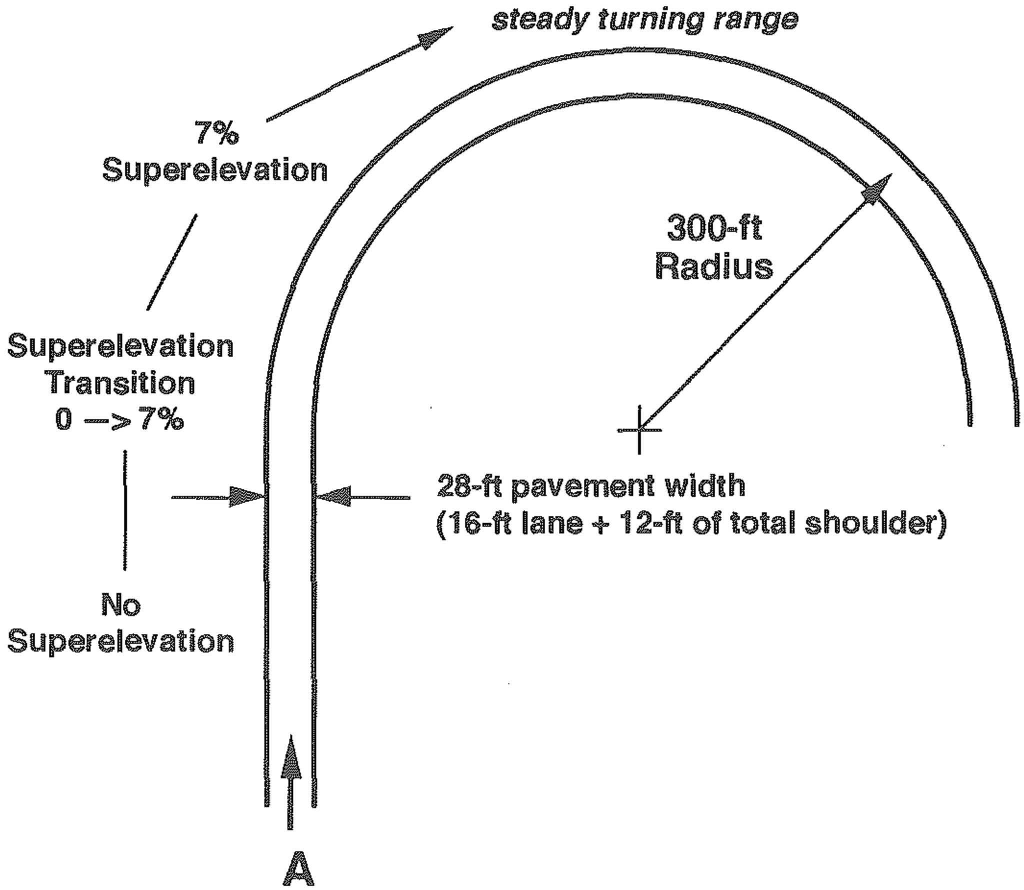
In this section, an example exit ramp geometry is used to evaluate how much offtracking occurs by a tractor/home combination on freeway exit ramps (as depicted in Figure 4-16), and whether or not significant differences are seen for homes of different width.

Figure 4-16. Turning Along Freeway Exit Ramps.



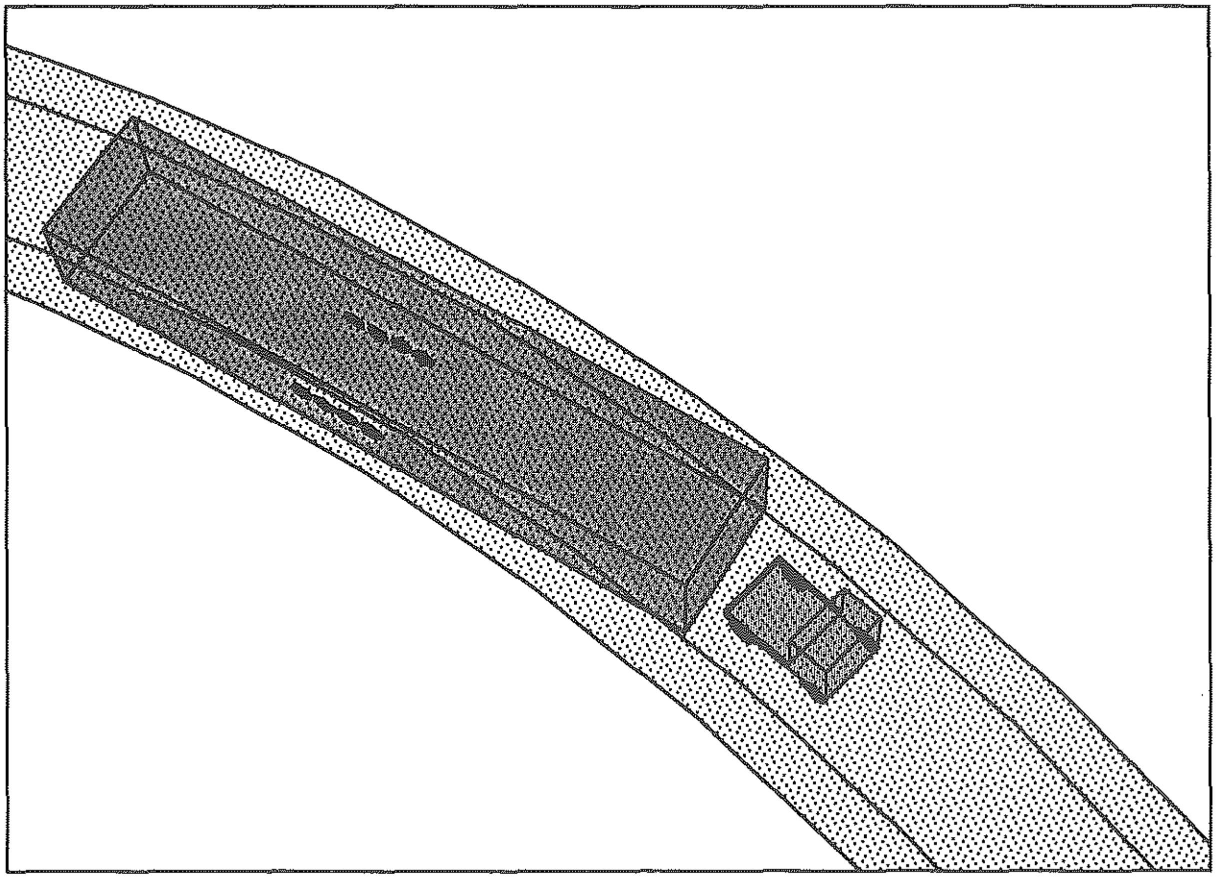
The exit ramp geometry used in this analysis is seen in Figure 4-17. The circular curve radius is 300 feet and the ramp is superelevated at 7%. Computer runs were conducted at both 25 mph and 8 mph to evaluate the influence of speed on the amount of offtracking displayed by the tractor/home combination along the exit ramp. Each run started from a straight-ahead direction at point A and was allowed to run until a steady turning condition was achieved midway or so through the curve.

Figure 4-17. Exit Ramp Geometry Used in the Computer Analysis.



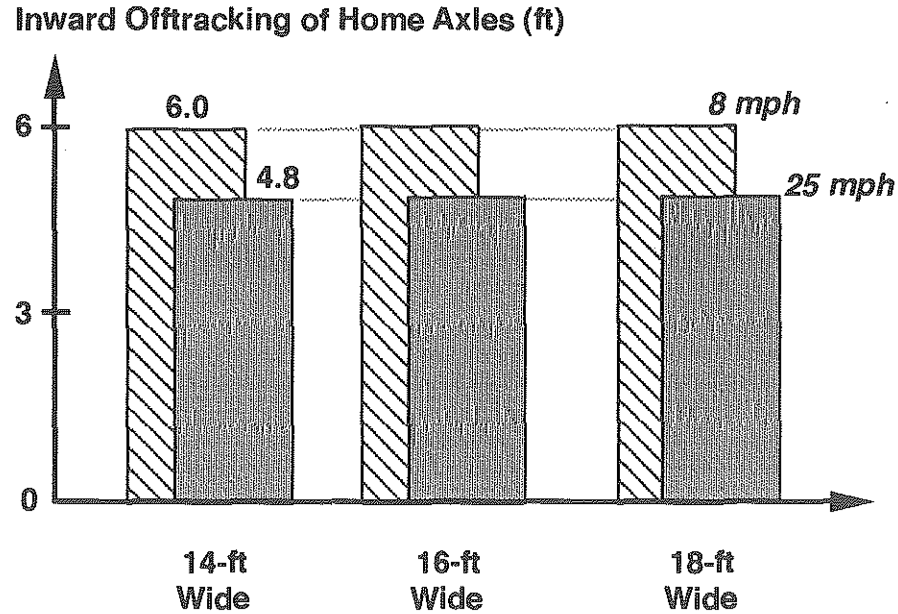
Lateral offtracking by the axle set on the home unit, away from the lane center and towards the center of the turn, was recorded in each case to evaluate the space requirements of the vehicle. Figure 4-18 shows an overhead view of a 16-ft wide tractor/home combination as it turns a superelevated 300-ft radius ramp having a 16-ft wide travel lane and two 6-ft wide shoulders. The vehicle is shown as transparent so that wheel locations can be seen. In Figure 4-18, the right-side wheels under the 16-ft wide home are travelling well into the 6-ft wide paved shoulder area on the inside of the curve. If vehicle speed is decreased to 10 mph or less along the curve, the home will swing approximately another 1 foot to its right toward the inner boundary.

Figure 4-18. Overhead Transparent View of 16-ft Wide Tractor/Home On Exit Ramp @ 25 mph.



In Figure 4-19, offtracking away from the lane centerline by the axle set on the home unit is plotted versus home width for two different speeds. All home lengths are 80-ft with the axle set centerline at the 2/3 point aft of the front of the home. As seen, the amount of offtracking by each home unit is approximately the same along the superelevated curve when travelling at the same speed. The primary effect on offtracking performance is related to speed. The 8 mph result is a good approximation to how each vehicle would also respond at speeds below 8 mph. As speed increases along the curve, centrifugal force causes the home unit to move more outward from its low speed position (which lies inward of the lane center) thereby diminishing the amount of inward offtracking displayed at low speeds. In all cases, the amount of lateral offtracking seen here does not present a problem of inadequate pavement width. For most freeway exit ramps having at least 26-ft or more of paved surface width (e.g., 16-ft lanes and 10 or more feet of total paved shoulder width), sufficient pavement should generally be available.

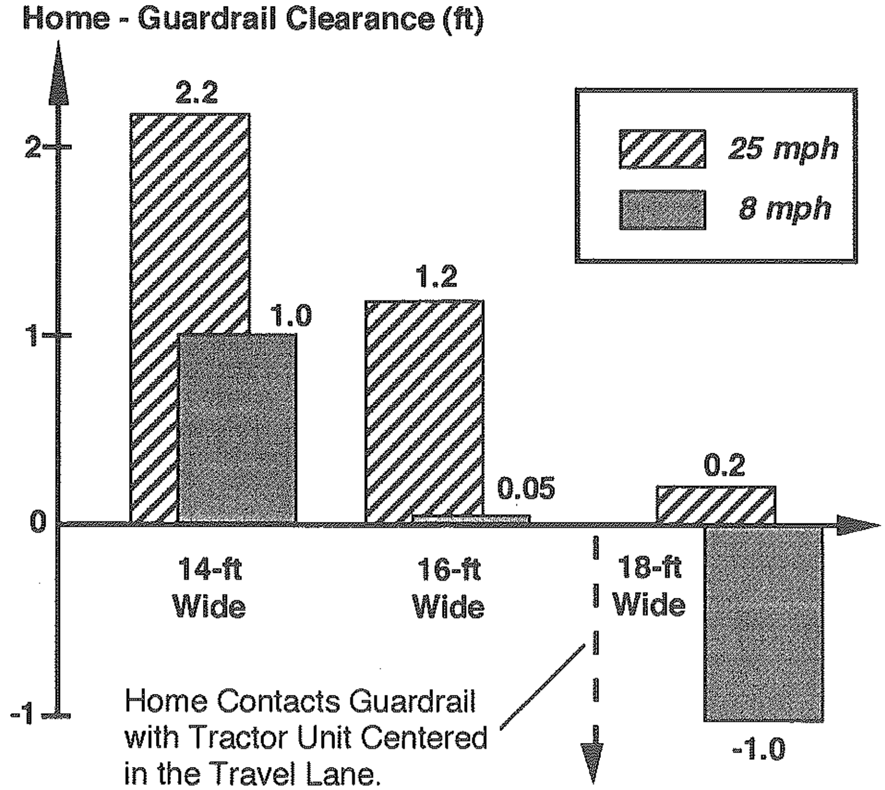
Figure 4-19. Tractor/Home Offtracking from Lane Centerline Along Freeway Exit Ramp @ 8 & 25 mph.



If home width is now included in the analysis, the amount of inside clearance between guard rail and home edge is seen plotted in Figure 4-20. This result assumes a 16-ft wide ramp lane, a 6-ft interior paved shoulder with flush guard rails, and the towing tractor travelling along the centerline of the 16-ft wide lane. (Some additional leeway is of course available if the tractor driver moves somewhat outward from the lane centerline.) The diminishing clearances seen in Figure 4-20 as home width increases are due only to the width increment, not to differences in offtracking performance per se of the tractor/home combinations.

The inside clearances are seen to be adequate for the 14-ft home, but approach relatively small levels for the 16-ft wide home on this type of exit ramp, particularly at low speeds. As mentioned, some leeway is available to the tractor driver by steering somewhat to the outside of the lane centerline. However, when adverse wind effects and/or normal driver steering irregularities are included as possibilities, lateral clearance margins still remain small for the 16-ft wide home. For the 18-ft wide home, the tractor driver must steer at least a foot or more outside the lane centerline to avoid contact with the guard rail at low speeds. An exit ramp that is 26 feet in width with flush guard rails would only provide 2 feet of "wiggle" room to the tractor driver towing an 18-ft wide home.

Figure 4-20. Home-to-Guard Rail Inside Clearance Along Exit Ramp for Different Home Widths. Tractor Unit Centered in Travel Lane.



5.0 Crosswind and Road Surface Influences Affecting Mobility and Space Requirements

Tractor/home combinations are presently permitted to operate in Michigan in wind conditions up to 25 mph. The purpose of this section is to evaluate the amount of lateral motion likely to occur when tractor/home combinations of different widths are subjected to crosswinds as large as 25 mph. The additional required space needed by the tractor/home vehicle will add to the total width requirements needed by each vehicle for operating under these permitted conditions.

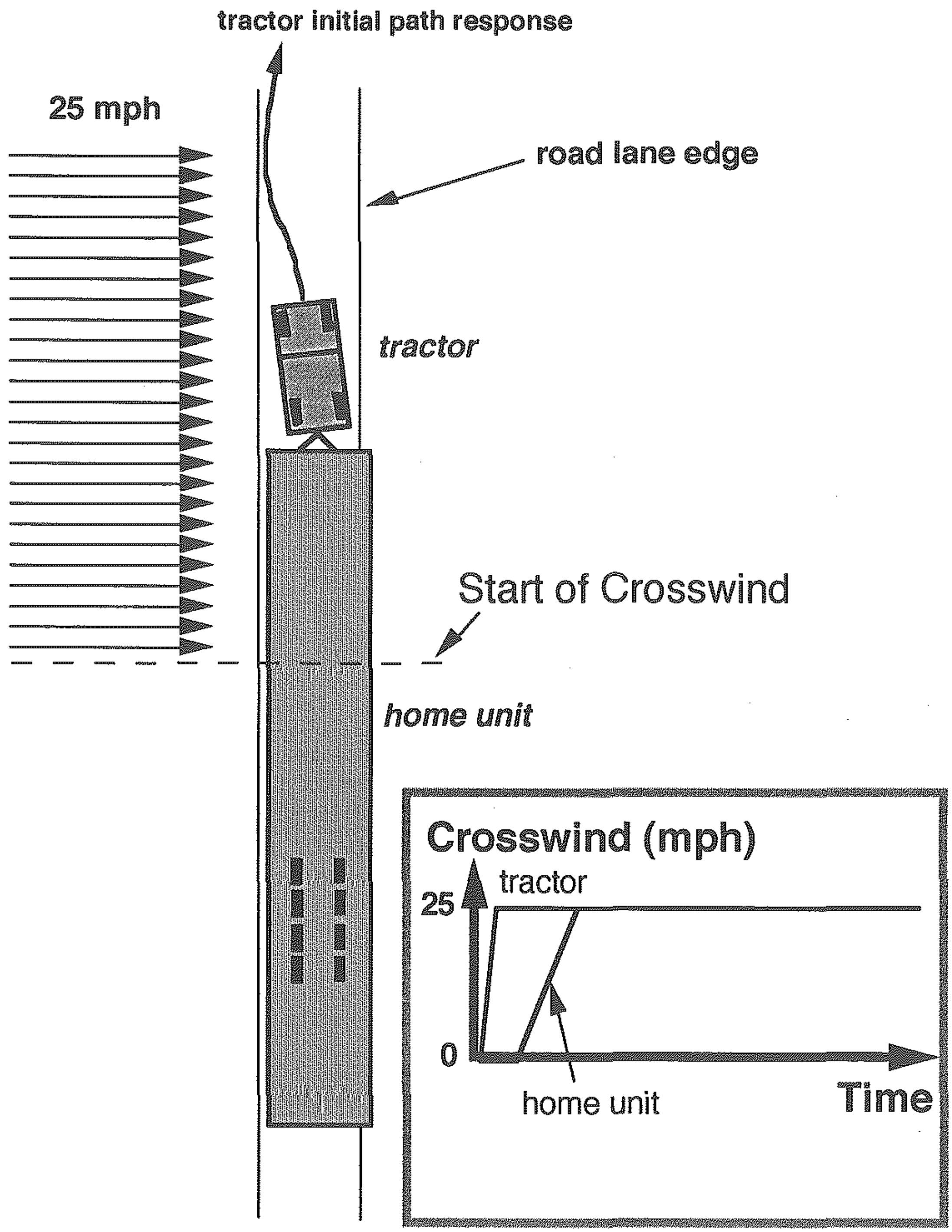
The computer simulation analyses used here rely on the UMTRI Phase 4 computer program [4]. The Phase 4 program has previously been modified to include crosswind aerodynamic effects. The aerodynamic properties of each tractor/home combination are treated as similar to those used in a previous study of crosswind disturbances to large commercial vehicles [5].

Idealized Uniform Crosswind Effects

To begin the crosswind analysis, an idealized crosswind having a constant 25 mph magnitude is utilized. Figure 5-1 illustrates the crosswind and the computer model scenario by which the tractor/home combination first encounters and then immerses itself into the uniform crosswind profile. The vehicle begins each maneuver by travelling in a straight-line direction immersed in still-air conditions. The vehicle then encounters a step-like stream of crosswind as portrayed in Figure 5-1. As the tractor and home unit move forward, they encounter the crosswind in a time-delayed and sequential manner. The crosswind is ramped-in over time for each body as illustrated in the inset diagram of Figure 5-1. This ramp-like relationship is used to approximate each unit's immersion into the crosswind stream as it moves forward. The rate of immersion (or slope of the ramp) is controlled to correspond with the forward speed of the vehicle train and the length of each unit.

The tractor path response seen in Figure 5-1 is a result of the the tractor/home aerodynamics as it first encounters the crosswind. Aerodynamic side forces, acting on the home unit and transmitted to the tractor through the ball hitch, cause the tractor to initially yaw up-stream into the wind. The driver model then responds to the disturbed tractor response by providing corrective steering back toward the initial travel direction, stabilizing the tractor within the lane. The small "lane-change" path response illustrated in Figure 5-1 summarizes this sequence of events and is a typical system response when first encountering a crosswind.

Figure 5-1. Simulated Crosswind Maneuver — Idealized Uniform Crosswind Profile.



In order for the vehicle to become stabilized in the constant crosswind, it must acquire a position and orientation similar to that depicted in Figure 5-2. The front ends of both the tractor and home unit rotate slightly into the wind in order to travel in a straight-line direction down the roadway. With the tractor centered in the lane, the home unit must swing somewhat further off center, and in the case shown in Figure, 5-2, further on to the shoulder. This basic response results in the entire tractor/home combination "crabbing," or moving forward in a direction slightly different than the direction it is pointed. Accordingly, the home's "effective width" is increased by the crosswind loading and rotation of the home unit. The net effect is that more lateral space is required for the tractor/home combination under such conditions.

To indicate how much additional space is required, Figure 5-3 shows the amount of additional offtracking space required by homes of three different widths. The calculations were conducted for two vehicle speeds and a constant crosswind of 25 mph. The results at 55 mph are of course due to the larger aerodynamic forces present under such conditions and are primarily included to illustrate the sensitivity of offtracking to vehicle speed. The small differences (0.1 ft) in offtracking due to home width are attributable primarily to weight differences in the home units.

To illustrate the sensitivity of offtracking distance to home density (or home weight per square foot), Figure 5-4 shows calculated results for an average density 16-ft x 80-ft long home unit weighing 29,000 lb versus a lighter unit having a lower density and weighing only 24,000 lb.

Figure 5-2. Simulated Crosswind Maneuver — Full Immersion into Crosswind and Steady-State Offtracking Response by Home Unit.

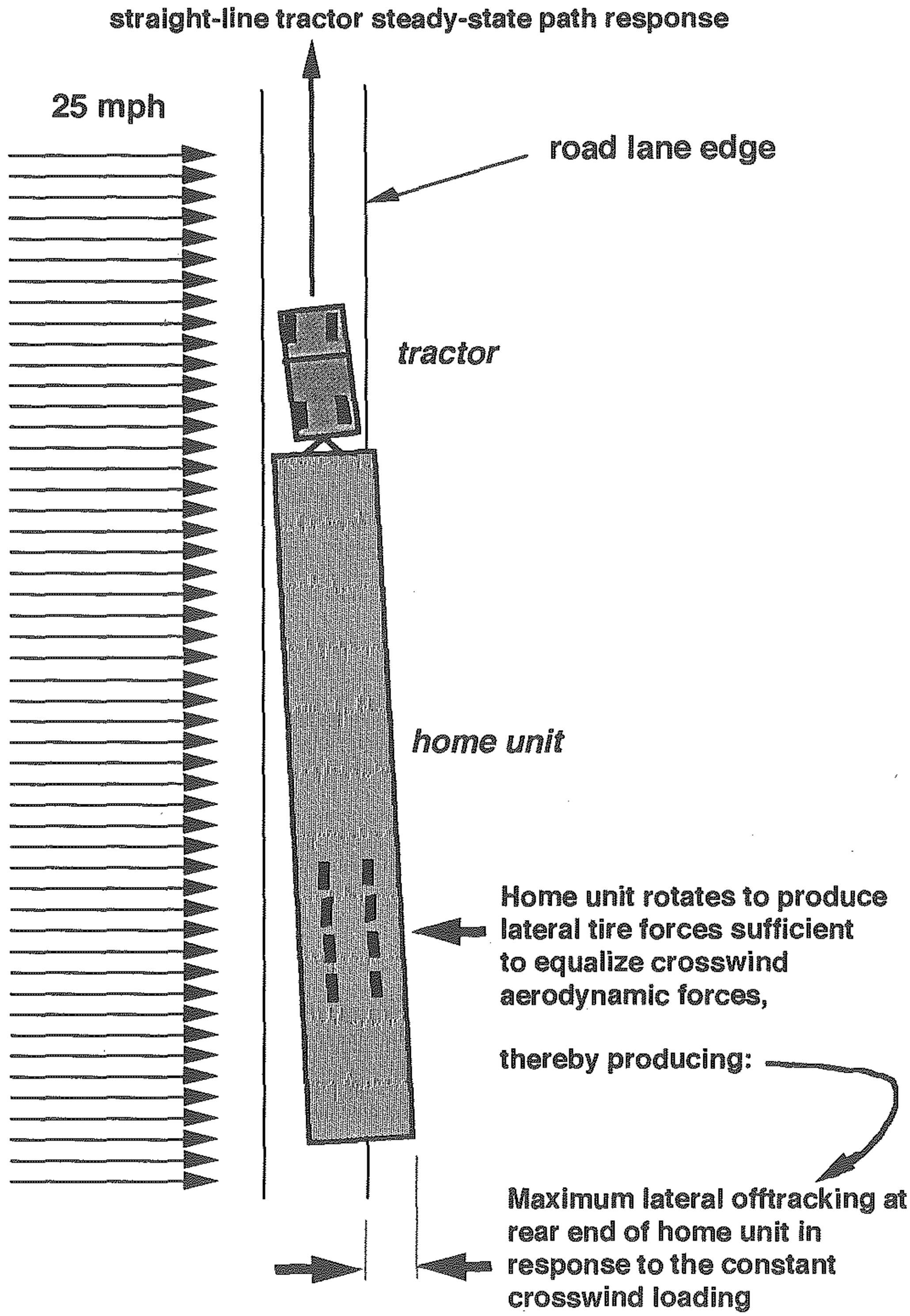


Figure 5-3.

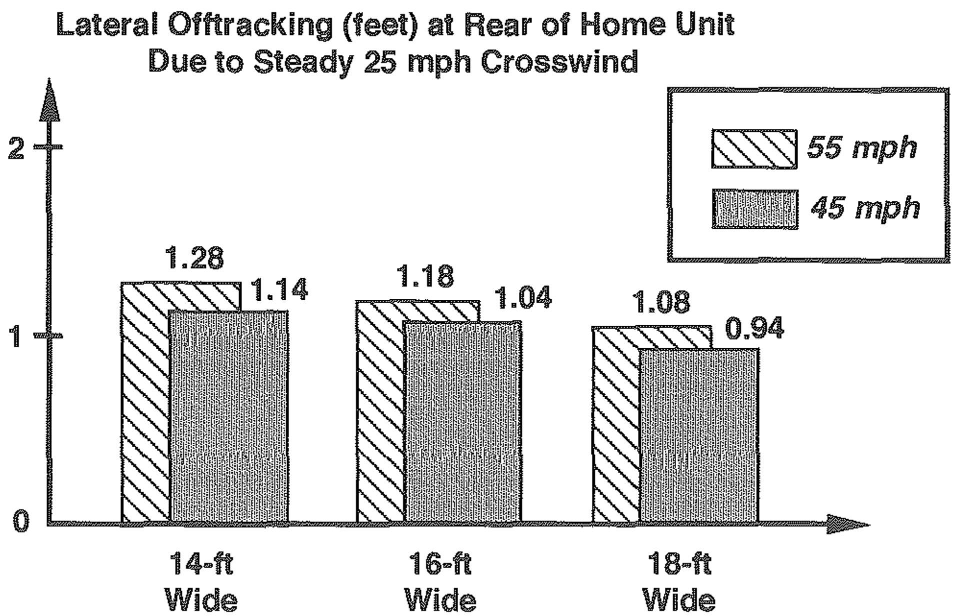
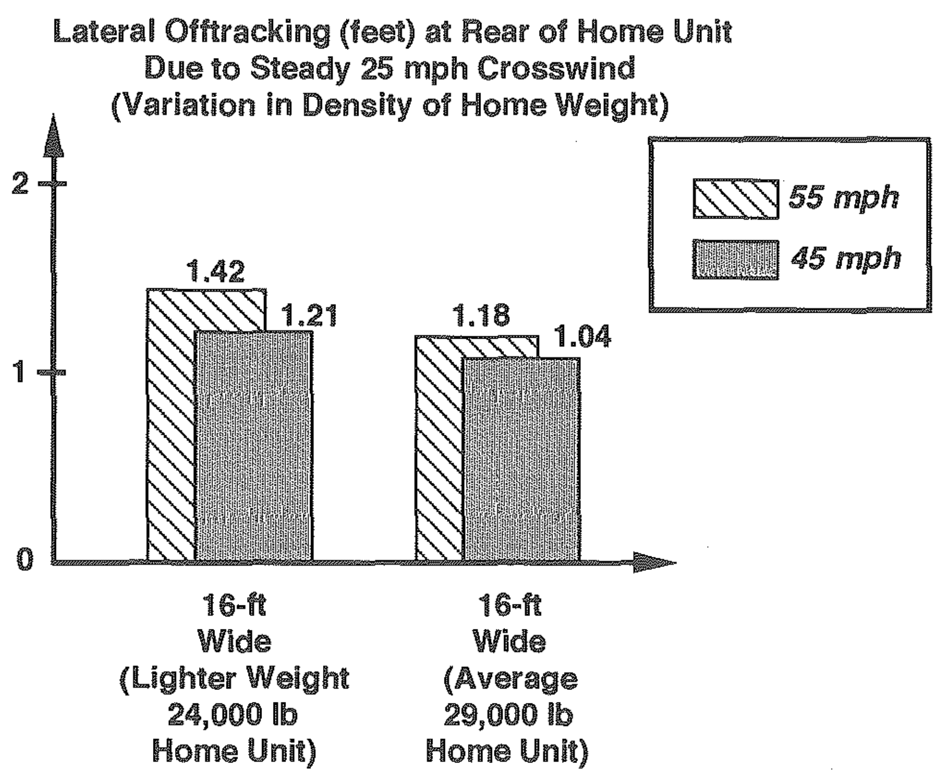


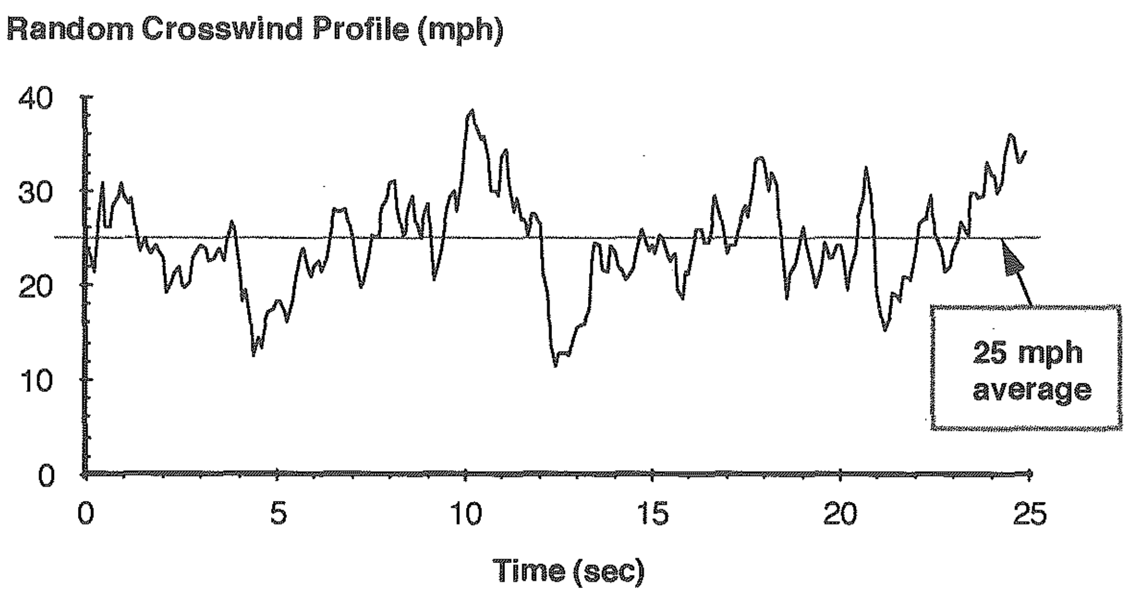
Figure 5-4.



Randomly Varying Crosswind

Although the constant crosswind results of the preceding discussion are useful in acquiring a basic understanding of how average tractor/home combinations respond in idealized crosswind conditions, the analysis is somewhat simplified because it ignores the influence of variability of natural wind profiles. To more accurately represent natural crosswinds that vary about an average value in a random-like manner, the idealized analysis of the previous section is extended here to include such effects. (Anemometers used by meteorologists and weather forecasters for measuring wind speeds are in effect measuring the average value of random-like wind profiles.) The idealized uniform crosswind of the previous section is modified here to include a random component superimposed upon the average 25 mph value used previously. Figure 5-5 shows a time history of a more realistic wind profile that, if measured by an anemometer, would also indicate an average reading of 25 mph.

Figure 5-5. Profile of Variable Crosswind Used in Simulation Analysis.



In order to evaluate the effect of a more natural and variable crosswind profile, calculations similar to those of the preceding section were conducted using the crosswind input seen in Figure 5-5. As before, the vehicle was driven in a straight-line direction and exposed to a crosswind — but one that now varied randomly about its average value. Each run lasted 25 seconds, thereby providing enough time to observe multiple cycles of the basic system response.

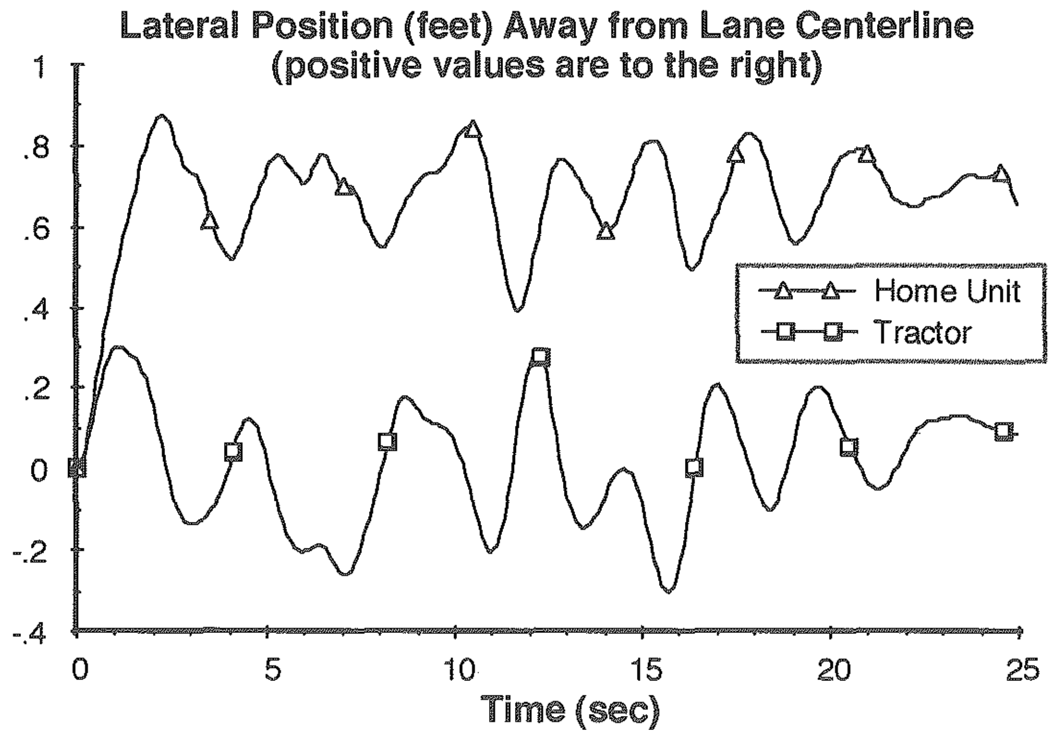
An example response is seen in Figure 5-6, which shows time histories of lateral position and heading angle for the tractor and the 16-ft wide home unit (at their respective mass centers). The tractor unit's lateral displacement varies about a value of zero, or the center of the lane. The home unit's position (mass center) is displaced about 0.7 feet on average. In the bottom graph, the heading angle of the home unit is seen wandering about a value of approximately -0.7 degrees. While these numbers seem relatively small, their effect when taken over the length of an 80-ft body can be significant.

To illustrate, the basic system responses observed in Figure 5-6 were reduced to a single lateral motion variable describing how much the rear end of the home unit moved in response to the same random crosswind. This quantity is seen plotted in Figure 5-7 and shows an average lateral displacement of 1.04 feet (the same as for the simplified 25 mph constant crosswind case). However, Figure 5-6 also shows how the rear end of the home unit changes with time when the crosswind is varying in a natural and random-like manner. In fact, peak values of lateral displacement are seen to routinely approach (and sometimes exceed) 1.5 feet for the random wind condition. Consequently, the lateral space requirements for operating in realistic 25 mph crosswind conditions are considerably greater than those suggested by the simpler analysis of the preceding section.

Also seen on the plot of Figure 5-6 is an indication of how much the lateral displacement variation grows if the hitch load on the tractor is reduced from the normal baseline value of 24% to a lower value of 18%. (The importance of hitch loads for tractor/home combinations is discussed in more detail in Section 6. However, it is noted here that the findings presented in Section 6 also have implications here with respect to crosswind excitations of tractor/home combinations when hitch load percentages are diminished from their normal values.) Accordingly, other factors such as ordinary in-use loading and weight distribution practices, intentional or inadvertent, can also play a role in contributing to additional degradation in offtracking performance by the home unit.

The significance of the crosswind results is that some additional width requirements are indicated and, that when added to any additional width requirement deriving strictly from increased home width, the total highway/shoulder space required may exceed availability along certain types of highways.

Figure 5-6. Tractor/Home Response to the 25 mph Random Crosswind. 16-ft Wide Baseline Home Unit. 45 mph Vehicle Speed.



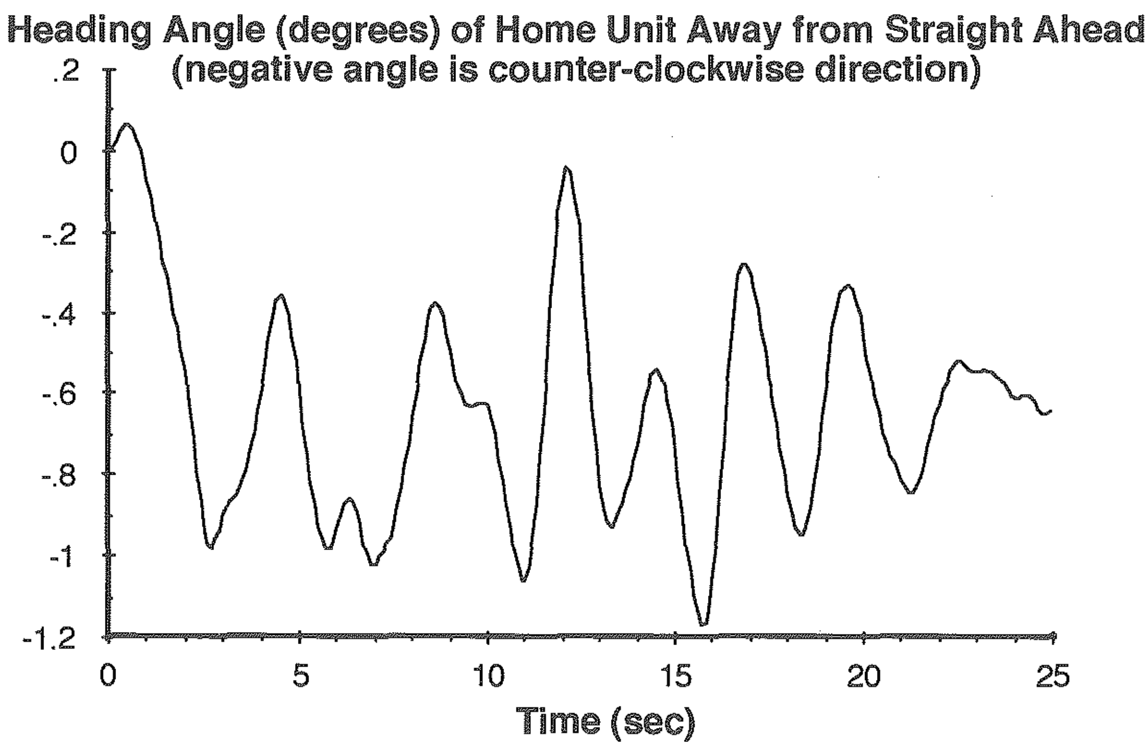
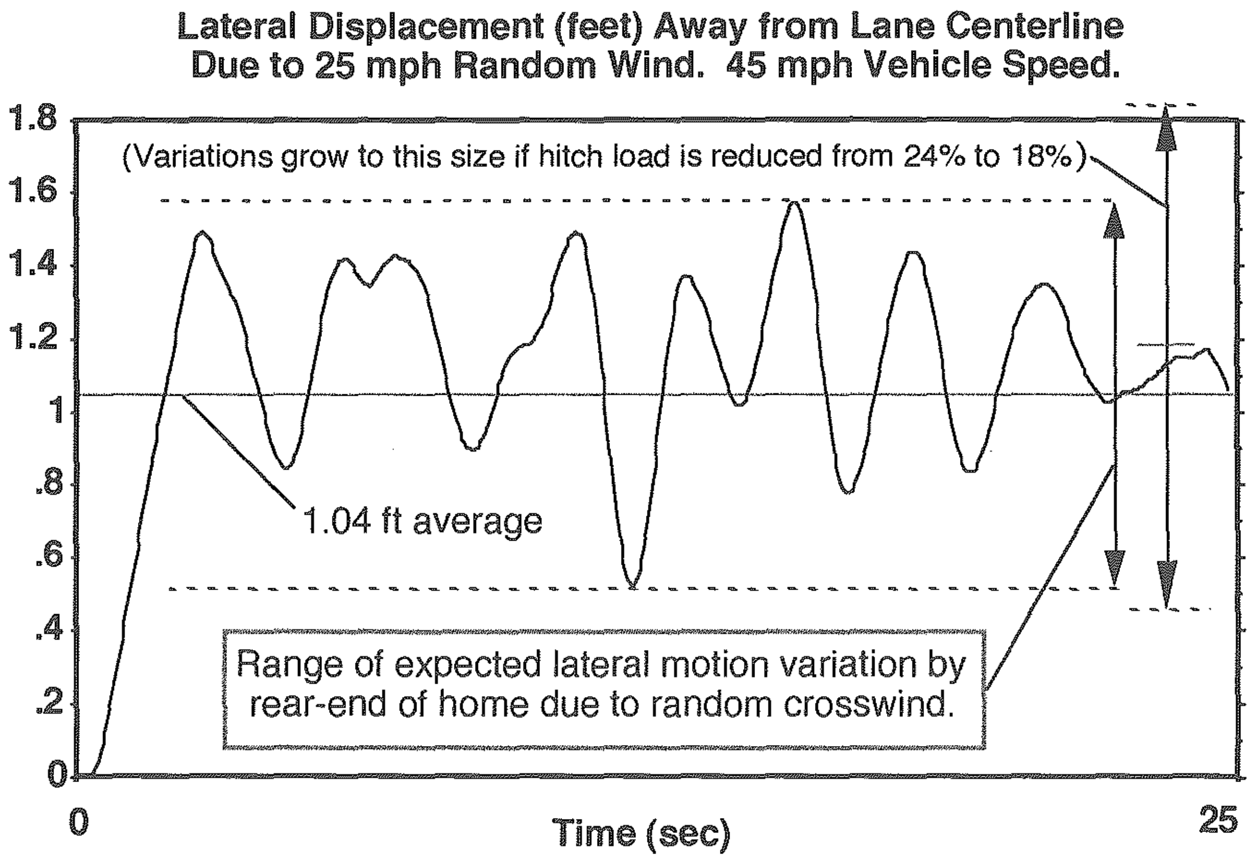


Figure 5-7. Lateral Movement (Wandering) at Rear-End of 16-ft Wide Home Unit in a Randomly Varying 25 mph Crosswind.



Highway Cross-Slope Effects

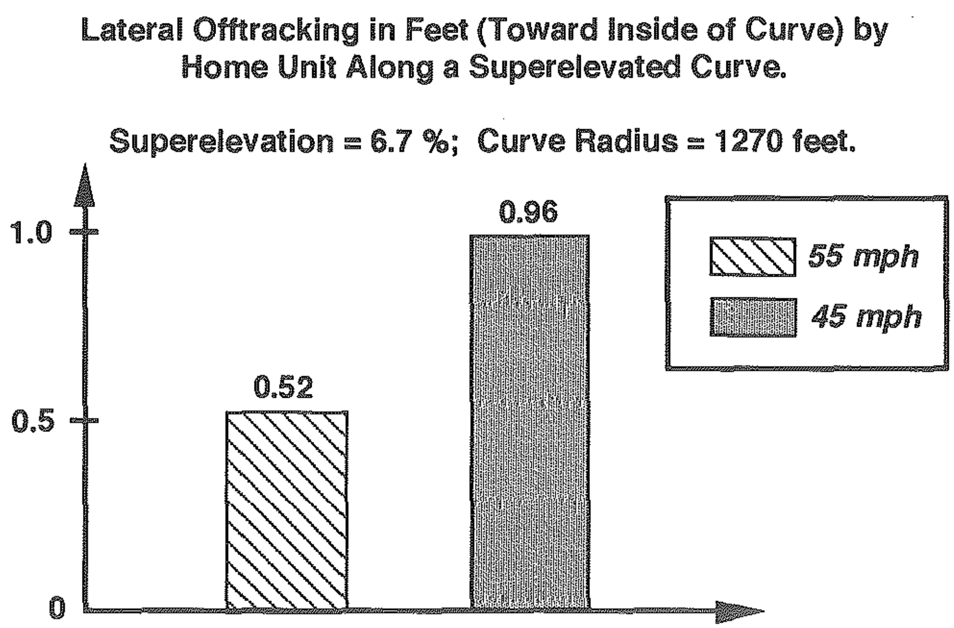
Most driving on highways is done along straight-line stretches that usually include some cross-slope for purposes of drainage. A representative amount of cross-slope might be 1% to 2%, depending upon the highway. To examine this particular effect on tractor/home offtracking while driving in a straight-line direction, computer simulations were conducted for these same conditions. The results indicated that the amount of offtracking for a 16-ft wide home unit (as well as 14-ft and 18-ft wide home units) is approximately 0.22 feet for a cross-slope level of 2%. Consequently the amount of offtracking is relatively small for normal amounts of highway cross-slopes, but should be accounted for in any total assessment of required space.

Offtracking on Superelevated Highway Curves

When travelling along connector-type superelevated curves on freeways, the amount of highway superelevation (or cross-slope) increases from that normally used on straight sections. To examine how turning along high-speed superelevated curves may influence offtracking requirements of tractor/home combinations, computer calculations were conducted using a representative highway curve geometry in Michigan. The particular geometry includes a straight tangent and circular ramp similar to that seen previously in Figures 4-17 and 4-18 for the exit ramp. However, in this case the curve radius is 1270 feet (instead of 300 ft) and the maximum amount of superelevation is 6.7% (instead of 7%). The normal speed of travel along such curves is also 45-55 mph.

The results from the computer calculations indicate that at a speed of 45 mph the amount of inward offtracking (toward the center of the turn) is approximately 0.96 feet. See Figure 5-8. If speed is increased to 55 mph, the amount of inward offtracking lessens to an amount of 0.52 feet (due to increased centrifugal acceleration tending to push the vehicle further outward from the turn center). These results are applicable to 14-ft, 16-ft, and 18-ft wide homes and do not suggest a significant problem of encroachment along such curves except in cases where outside shoulders are insufficient in width, thereby requiring the tractor home combination to encroach into passing lanes. Again, in such cases, this will be more of a problem with 16-ft and 18-ft wide homes because of their overall greater widths.

Figure 5-8. Offtracking by All Home Units Along a Superelevated Curve.



6.0 Braking Performance and Hitch Load Practices Affecting Directional Stability

Two topics related to operational practice and design are examined in this section. The first, braking performance, examines what levels of braking performance may be expected from tractor/home combinations on dry pavements and the jackknifing response that can occur if over-braking by the tractor driver is used in emergency conditions.

The second issue, hitch load practice, illustrates the type of oscillatory behavior that can occur at highway speeds if hitch loads on the tractor are too light.

Both of these topics are important with respect to the directional stability of tractor/home combinations and will be addressed in the context of recommended practices.

Braking Performance Issues

Tractor/home combinations typically rely upon the braking power of the towing tractor unit because little braking is provided by the home unit wheels (e.g., electric brakes on one home axle). Since the tractor unit typically represents less than half of the total vehicle weight, some degradation in braking performance of tractor/home combinations, relative to nearly all other vehicles on the highway, is expected.

To examine this issue, braking maneuvers were conducted with the UMTRI Phase 4 computer model to calculate stopping distances and vehicle responses for different levels of applied braking effort. The nominal braking maneuver is seen in Figure 6-1. The maneuver begins with the vehicle heading in a straight-line direction at a speed of 45 mph. A slow and mild lane-change steering maneuver occurs over a travel distance of approximately 300 feet. One second after starting the lane change, a constant-pressure brake application is applied to bring the vehicle to a stop. (The lane-change is used to provide a more realistic on-highway scenario requiring some mild maneuvering during the braking stop.)

Several runs were conducted with brake pressure incremented between runs. At the end of each run, stopping distance from the time of the brake application was recorded to evaluate the performance. This sequence was repeated for home units having widths (and corresponding weights) of 14-ft, 16-ft, and 18-ft. In each case, a maximum brake pressure is obtained that allows the vehicle to brake to a stop in a stable manner. If that maximum brake pressure is exceeded, an unstable jackknife response ensues causing the tractor to rotate around the hitch point towards the home unit. See Figure 6-2. If a tractor driver is

Figure 6-1. Braking Maneuver Used to Evaluate Tractor/Home Combination Braking Performance.

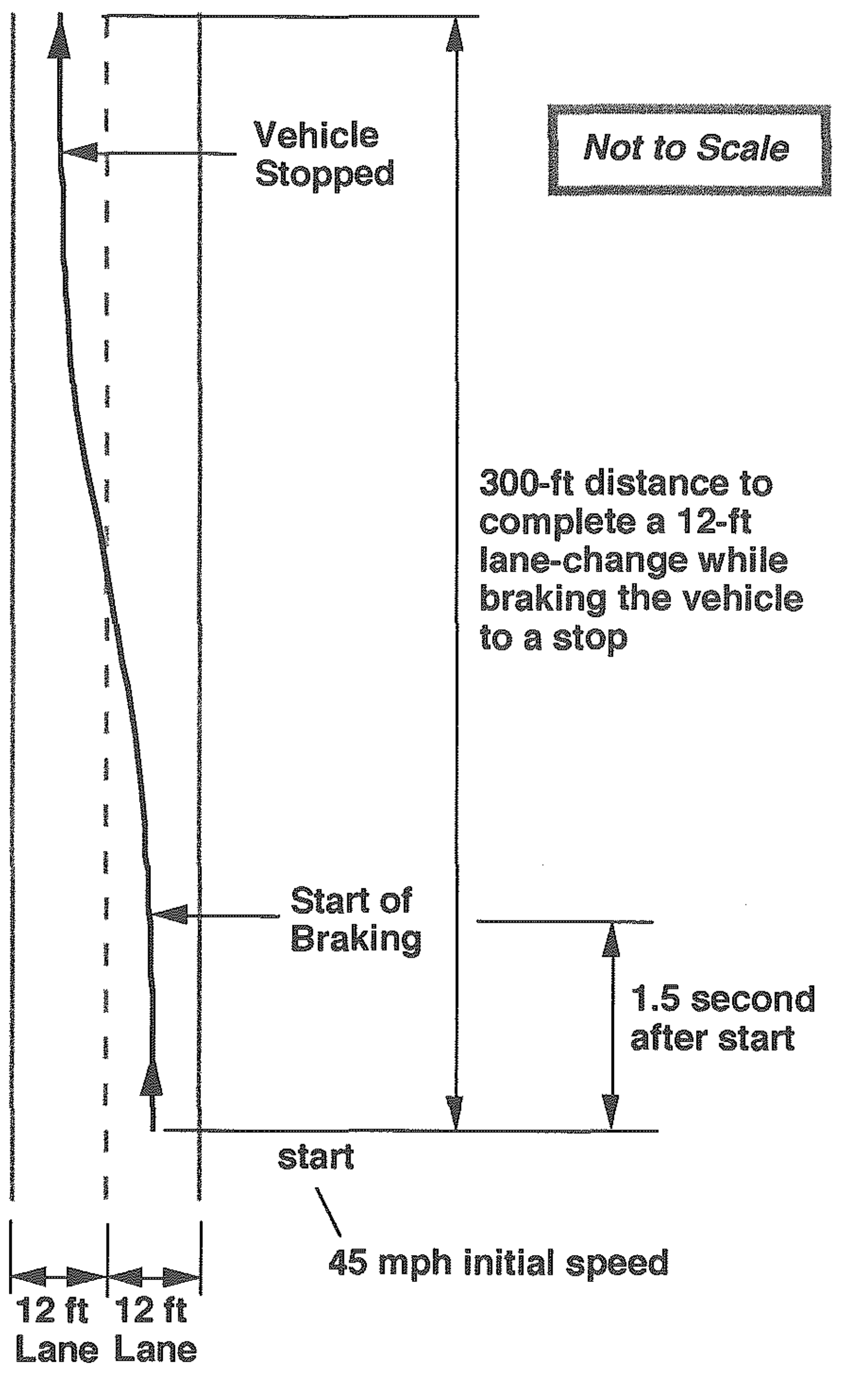
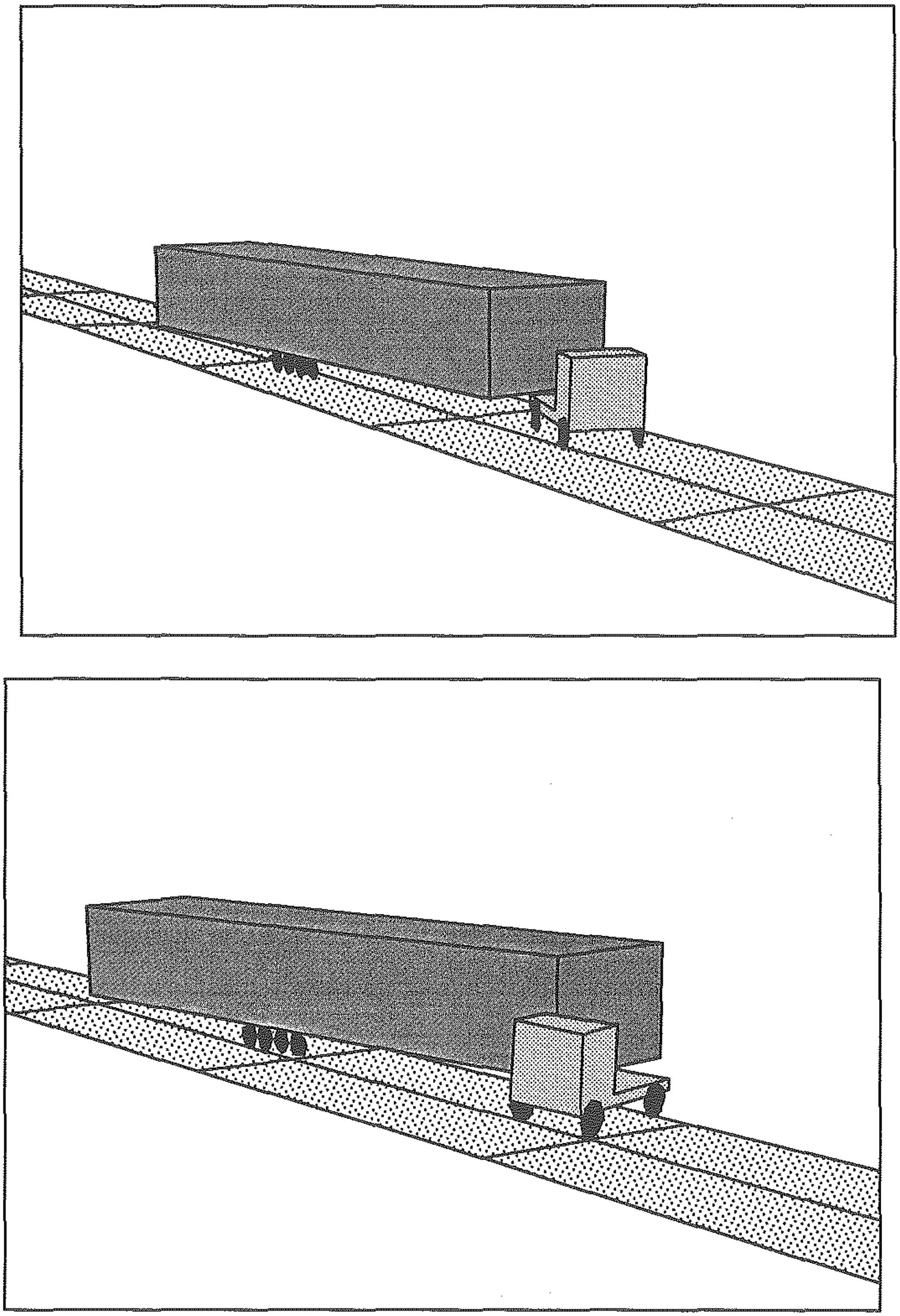


Figure 6-2. Jackknife Braking Instability in Tractor/Home Combinations Caused by Over-Braking in Emergency Stops.



able to quickly release the applied pressure at the start of the instability, directional control of the tractor unit can likely be regained. However, stopping performance is then degraded. Consequently, the practical braking performance limit is determined by the maximum brake pressure that can be applied — just shy of that causing an unstable jackknife response.

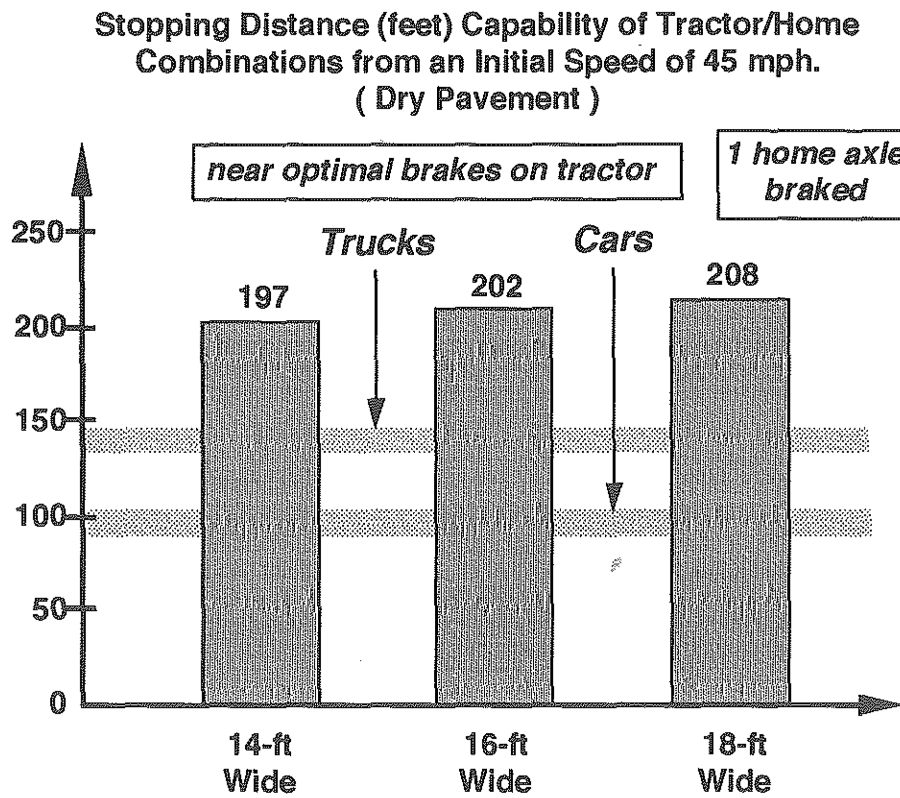
The jackknife tendency is enhanced in tractor/home combinations because the demand for braking the entire vehicle falls primarily on the tractor unit, thereby increasing the chances of wheel locks (the primary de-stabilizing mechanism). Tractor-dominated braking likewise contributes to the home unit over-running the tractor during hard stops. The very rearward location of the hitch point on the tractor is also a contributor insofar as providing a longer lever arm through which over-running forces from the home unit can act to disturb and rotate the tractor unit.

> (Although this response may seem rare, an example of a near jackknife incident did occur during the field study and was recorded on videotape. See Figure A.24 sequence in Appendix A. An oncoming vehicle in a suburban area turned suddenly in front of the towing tractor. The tractor driver reacted by applying the brakes fairly aggressively. Several wheel locks occurred on the tractor — as evidenced on the videotape by several seconds of tire smoke and sudden swerving at the front end of the tractor/home combination. The driver then released the brakes and regained control of the vehicle.)

In Figure 6-3, the minimum stopping distances achieved for each home width, using the braking maneuver seen in Figure 6-1, are seen in a bar chart. The brake proportioning on the tractor unit was assumed to be nearly optimally distributed between front and rear axles for these calculations and were conducted with one home axle also being braked. Also seen on this chart are bands of representative stopping distances for both passenger cars and heavy trucks, also from initial speeds of 45 mph. Corresponding stopping times are seen in Figure 6-4.

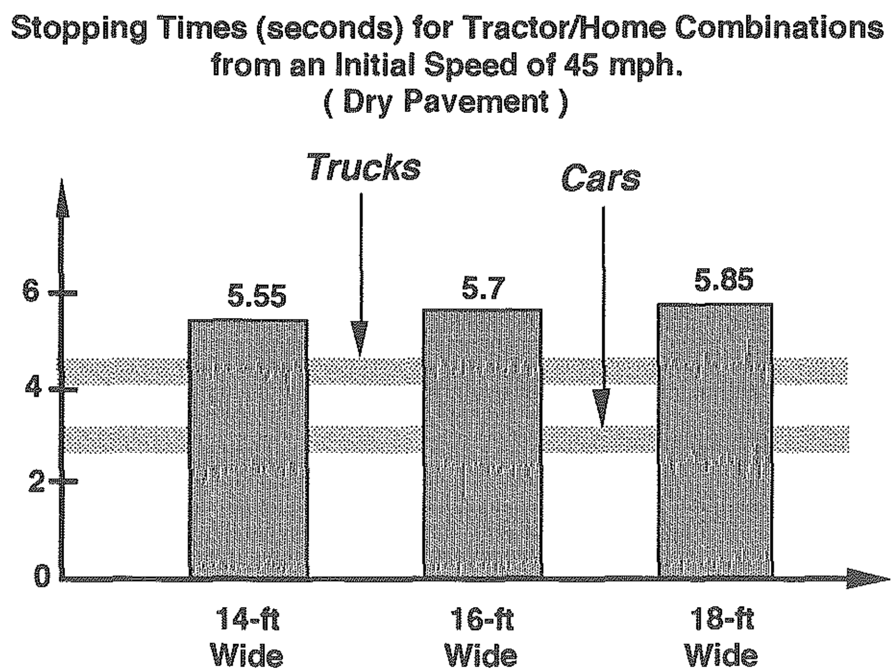
As home width increases, stopping distances and times lengthen slightly. This is a direct result of the increased weight of the larger width homes and the limited availability of brake torque retardation supplied by the tractor and home units. (The indicated degradation with increased home width would be larger if no weight transfer occurred between the home unit and tractor during braking. However, because wider homes do transfer some of their additional weight on to the tractor unit during braking, the amount of degradation in braking performance is lessened.)

Figure 6-3. Stopping Distances for Tractor/Home Combinations and Other Highway Vehicles from 45 mph.



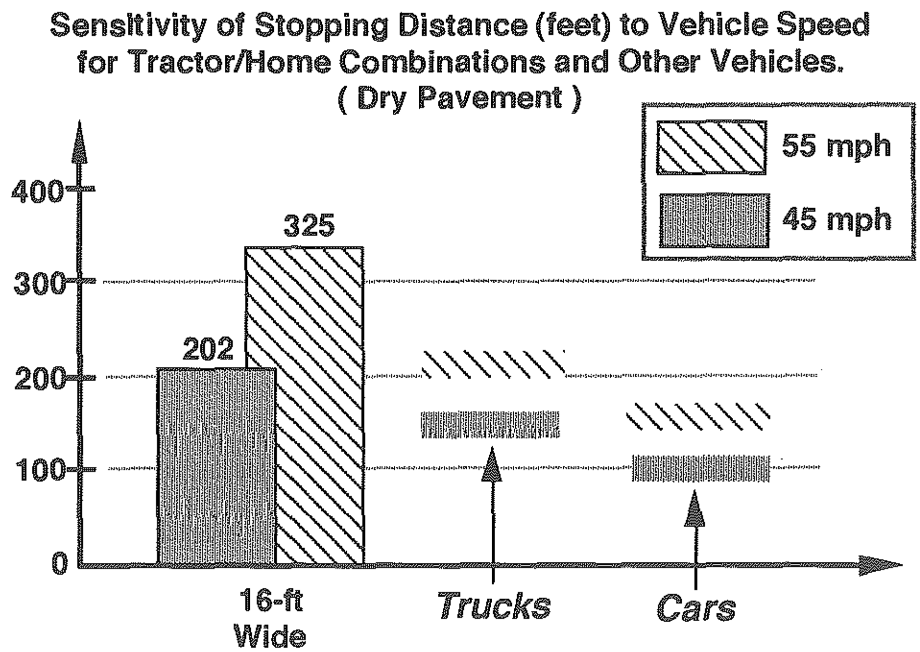
An important point here is that the best braking performance of most tractor/home combinations is far less than that typically displayed by passenger cars and heavy trucks that operate on the same highways. For example, stopping a tractor/home combination from an initial speed of 45 mph in the indicated maneuver of Figure 6-1 requires about 200 feet of stopping distance for each of the tractor/home combinations. This compares with passenger cars that would normally require about half that same stopping distance and heavy trucks that would need about 2/3 the same distance. Consequently, there is a significant disparity in stopping capability between tractor/home combinations and their highway counterparts. Furthermore, an additional concern is raised for tractor/home combinations since over-braking by the tractor driver (inadvertent or emergency-induced) can produce an unstable jackknife response, thereby reducing the margin for error and controllability during braking conditions.

Figure 6-4. Stopping Times for Tractor/Home Combinations from 45 mph.



If the vehicle speed is increased from 45 mph to 55 mph, the required stopping distance for the average weight 16-ft wide home increases from about 200 feet to a value of more than 300 feet as seen in Figure 6-5. Stopping distance is especially sensitive to vehicle speed as Figure 6-5 clearly illustrates. These distances will be slightly longer for heavier 16-ft wide homes and slightly shorter for lighter home units. (Comparable changes in stopping distances occur for 14-ft wide and 18-ft wide homes when speed is likewise increased to 55 mph.)

Figure 6-5. Stopping Distance Sensitivity to Vehicle Speed.



These observations lead to recommendations regarding maximum allowed speeds and required buffer space between the lead escort vehicle and tractor/home combinations. Clearly, additional braking space is required by such vehicles for sudden stopping along highways. The most practical means for providing this additional space is with a lead escort vehicle. The lead escort vehicle, in cooperation with the tractor driver, should maintain the size of the buffer zone based on travel speed. Specific recommendations are offered in Section 7.0.

Hitch Load Practices

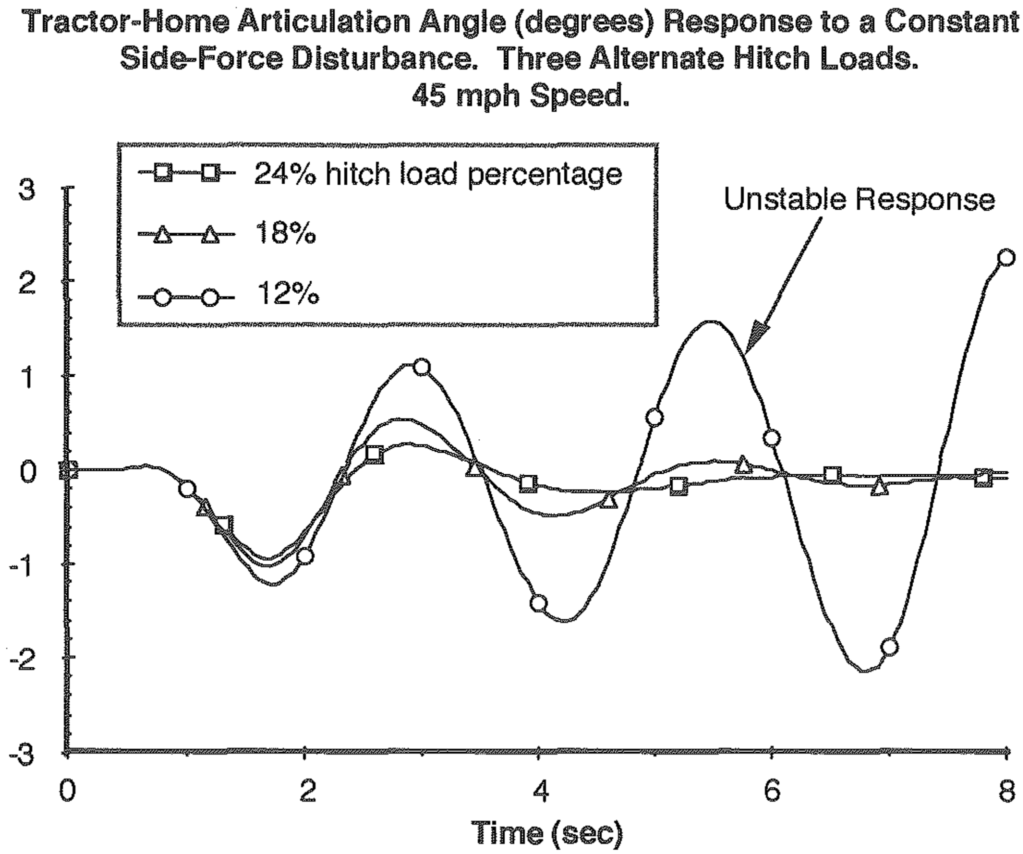
The axle load measurements conducted by the Michigan State Police for this study and appearing in Section 2 suggest that, on average, the hitch load levels observed were approximately 24% of the total home weight. That is, 24% of the weight of the home unit was being applied on to the tractor unit at its hitch point (e.g., a home unit weight 28,000 lb would have about 7,000 lb of its weight carried by the tractor hitch and 21,000 lb by its own wheel set). Information obtained from one housing manufacturer also indicates that their design specifications regarding axle placements on the home unit (2/3 of the way aft of the front end) should produce hitch load percentages of approximately 24%, provided that the home unit is manufactured with a uniform fore-aft weight distribution.

Some variance in these percentages can and does occur. The extent to which the hitch load is carefully controlled is not clear. Estimates performed in Section 2.0, using the State Police axle measurements and an assumed 16,500 lb tractor weight, indicate possible variations in hitch load percentages from a low of 16% to a high of 32%. (Tractors weighing more or less than the 16,500 lb assumed weight would modify this range, depending upon their exact weight.)

The importance of this issue is that computer model calculations conducted with the UMTRI Phase 4 program indicate that a strong sensitivity exists between oscillatory behavior of the tractor/home combination and hitch load percentages. The calculations show that lightening the hitch load (i.e., reducing the hitch load percentage) produces unwanted oscillations of the home unit at highway speeds. If the percentage is reduced to levels of approximately 12%, the oscillations grow successively in magnitude and the tractor/home combination becomes unstable. At hitch load levels of 18%, the system is mildly oscillatory but stable. If speed is increased from 45 mph to 55 mph the oscillatory behavior worsens. Consequently, the range of acceptable or desirable hitch load percentages is relatively narrow. Furthermore, this percentage can be influenced adversely by unusual loading of home units or nonuniform weight distributions.

Figure 6-6 shows a set of example results from the computer model calculations and the influence of hitch load. The plots appearing in Figure 6-6 show articulation angle (angle between the tractor and home unit longitudinal axes when viewed from an overhead position) versus time. The three plots correspond to hitch load percentages of 24%, 18%, and 12% for a 16-ft wide home. In each case, the tractor/home combinations are moving initially in a straight-line direction and are then disturbed by a constant crosswind side-force. (These results apply regardless of the type of disturbance. Driver steering inputs absent of any wind could also be used to illustrate the same phenomena.) Following the initial disturbance, the plots should normally die out and return to near-zero levels if the vehicle is stable and well behaved. As seen, the 24% case does this very rapidly; the 18% case also returns to zero but contains some additional oscillations; the 12% case is unstable with each successive oscillation larger than the last.

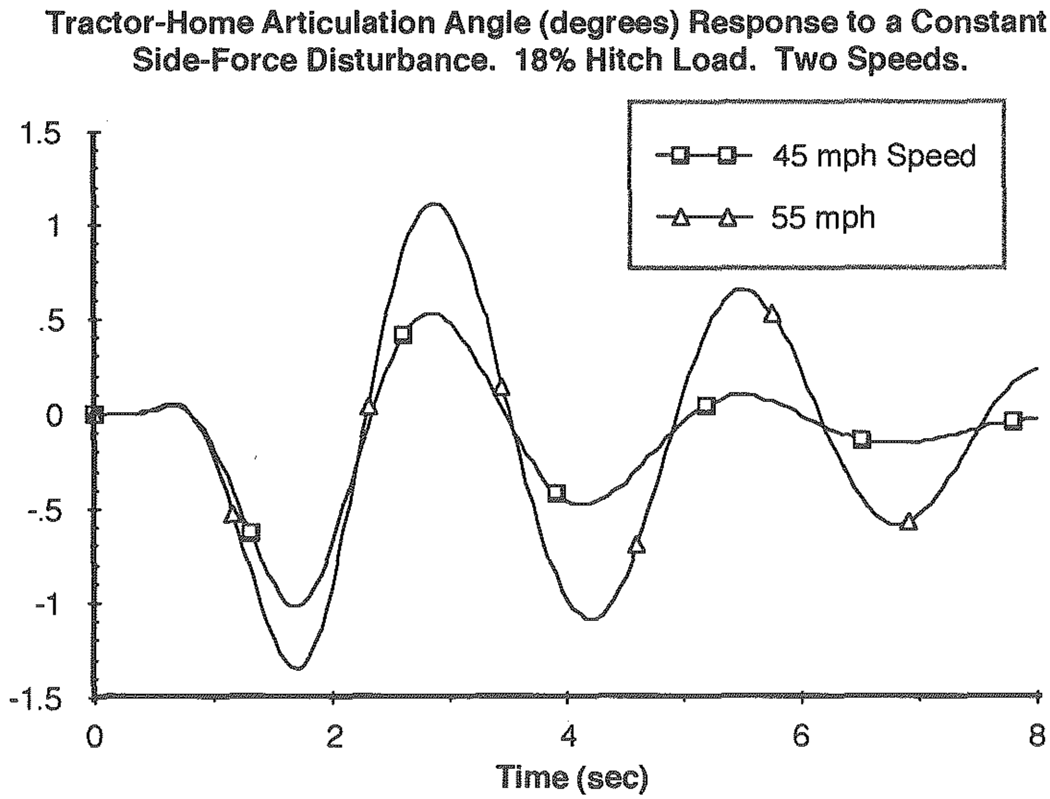
Figure 6-6. Influence of Hitch Load Percentages on System Oscillatory Behavior. 16-ft Wide Home.



In Figure 6-7, the influence of vehicle speed is shown for the case of the 18% hitch load. As speed is increased from 45 mph to 55 mph, the degree of oscillatory behavior is increased, indicating a diminished level of stability at greater highway speeds. This increased oscillatory behavior with higher vehicle speeds is also observed for other hitch loads and home widths.

The question of how home width per se affects these results is seen in Figure 6-8. At the design hitch load of 24% (top graph), all responses are well behaved, damping out quickly in less than two cycles. As home width increases, only slight degradations in damping are observed. For the 18% hitch load case (bottom graph), all three home widths exhibit more oscillatory behavior, with the wider home units, as above, showing slightly greater oscillatory tendencies.

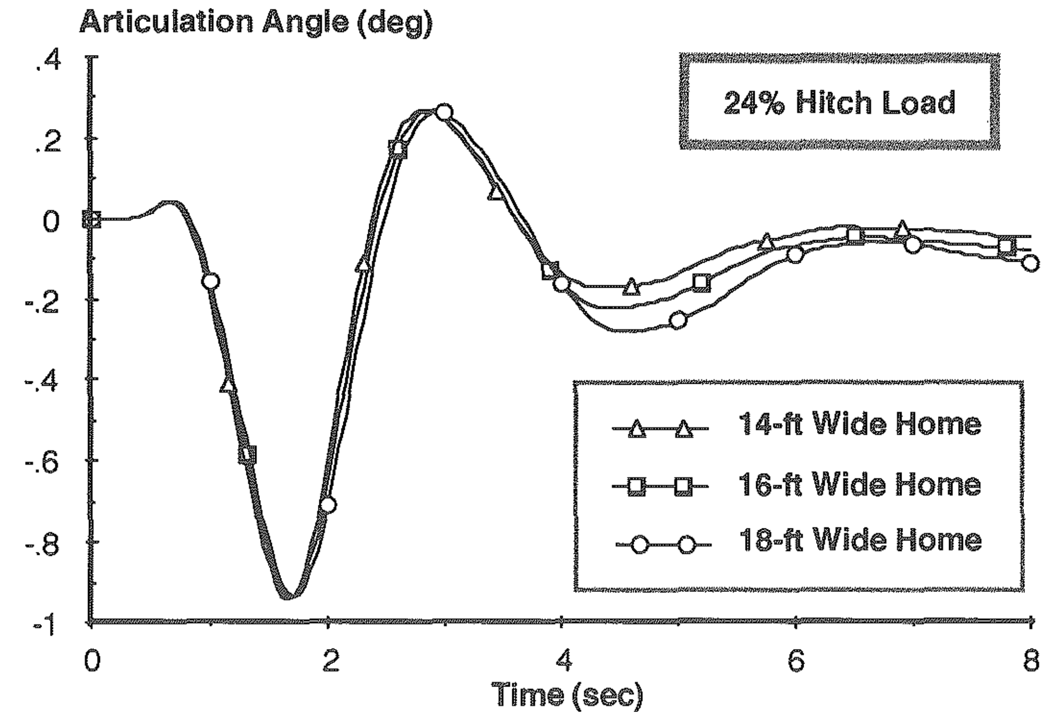
Figure 6-7. Influence of Vehicle Speed on System Oscillatory Behavior with Hitch Load Percentages of 18%. 16-ft Wide Home.

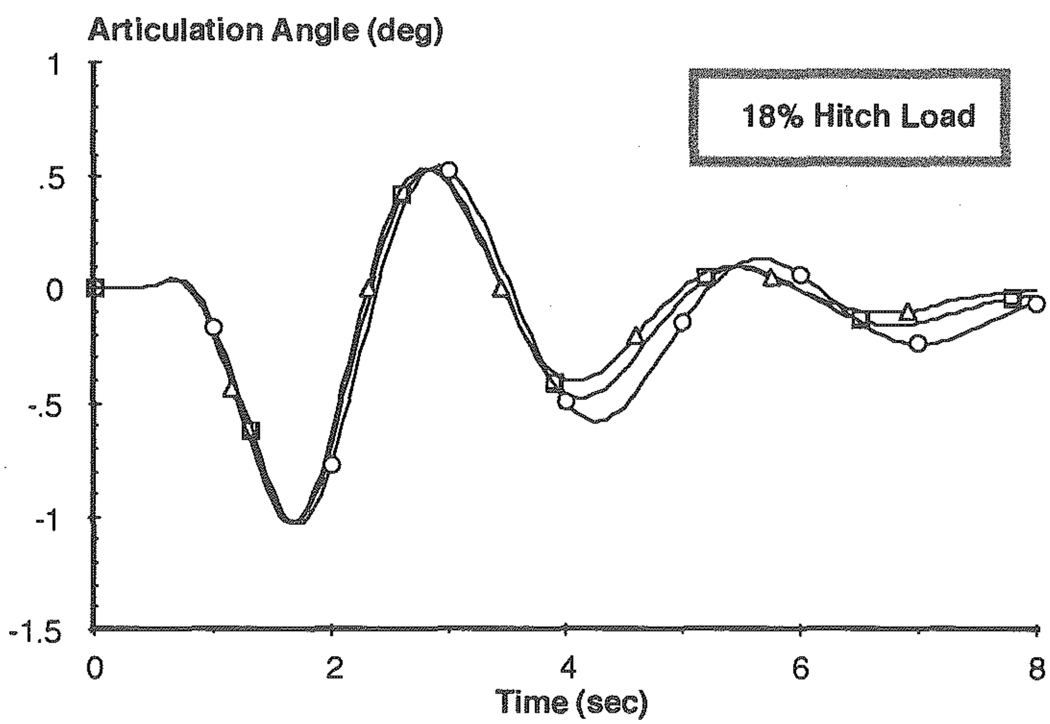


While these results show some differences between home widths, the primary concern here relates to control of hitch load percentage and vehicle speed. Opportunities for additional side-to-side wandering for homes of all widths are increased and likely to occur if hitch loads are inadvertently reduced below 20% and/or when vehicle speeds increase beyond 45 mph or so.

A recommended method for maintaining a well damped and controllable home unit is through use of a 24% (+/- 4%) hitch load and keeping vehicle speeds at or below 45 mph. (Note that this hitch load percentage for tractor/home combinations is about twice that normally recommended for much smaller car/trailer combinations that typically employ a "10%-15% rule of thumb" for hitch loads.) Unexpected oscillations that do develop during highway travel can be diminished by slowing down and/or correcting any adverse weight distributions through forward movement of larger cargo within the home unit. The period of oscillation (between cycles) will be about 3 seconds and will normally develop slowly, thereby leaving ample time in most situations for drivers to recognize and correct the problem if it does occur.

Figure 6-8. Influence of Home Width on Vehicle Oscillatory Behavior for Two Hitch Load Percentages.





7.0 Conclusions and Recommendations

— • — *Conclusions* — • —

The conclusions seen here summarize the basic findings described in Sections 2 through 6 of this report. (Those conclusions for which home width per se plays a significant role are explicitly noted. Those conclusions that do not identify home width explicitly as a factor may be applied to homes of all widths, i.e., 14-ft, 16-ft, and 18-ft wide units.) Recommendations appear in the section immediately following the conclusions.

The results obtained from the field study observation data in Section 3 indicate that:

- During passing events on multilane divided highways, 16-foot wide tractor/home units encroached into the passing lane more than 14-foot wide units on average. Specifically, 16-foot wide units were observed encroaching an average 40.3% of the time for each passing event, while 14-foot wide units were observed encroaching an average of only 20.5 % of the time for each passing event.

- On multilane divided highways no significant relationship was found between the shoulder encroachment behavior of passing vehicles and the width of the tractor/home unit being passed.

- Passing vehicles (on multilane divided highways) were found to encroach onto the shoulder nearly two-thirds of the time regardless of the width of the tractor/home unit being passed.

- On two-lane, undivided roadways, drivers approaching an oncoming 16-foot wide tractor/home unit were more likely to use the shoulder than were drivers approaching 14-foot wide units. Approximately 57% of oncoming drivers used the shoulder when approaching a 16-foot wide unit; only 32% of drivers used the shoulder when approaching an oncoming 14-foot wide unit.

- The collected data also show that tractor/home units of both widths regularly travel in excess of the maximum speed specified on their travel permits. The 16-foot wide units were found to be travelling at almost the same average speeds as the 14-foot wide units.

- The field data collected under this study were focused almost exclusively on home shipments that entered the state from manufacturers and were travelling to dealer sites. No data were collected for home shipments that originated at in-state dealers and travelled to the final site locations of the homes. Consequently, the data reported here do reflect the more idealized travel portion of home shipments in the state that make use of higher quality freeways and roads. Even under these more ideal travel conditions, the data collected under this study still display a significant amount of time and miles spent on two-lane undivided highways. It should likewise be noted that the second portion of most deliveries (dealer to site) rely to an even greater extent on two-lane undivided secondary highways and county roads.

Videotape analyses from the field study completed since the Interim Report (end of Section 3) indicate that:

- 16-foot wide homes encroach into the left adjacent lane more often than do 14-foot homes.

- 16-foot homes use the right shoulder a greater proportion of the time than do 14-foot homes.

- Homes of both widths are more likely to encroach into the left adjoining lane when travelling on roadways with 11-foot lanes than on roadways with 12-foot lanes.

- Encroachment into the left adjacent lane is related to the condition of the right shoulder such that the poorer the condition of the right shoulder, the more time homes spend encroaching in the left adjacent lane.

- Homes of both widths spend less time using the right shoulder when that shoulder is in poor condition. This is the probable reason greater left adjacent lane encroachments were observed for roadways with right shoulders in poor condition.

- Homes of both widths are more likely to spend time encroaching into the left adjacent lane on two-lane roadways than multilane divided highways.

- Both cars and trucks are more likely to use the shoulder when passing 16-foot wide homes than when passing 14-foot wides, and trucks are even more likely to use the shoulder when passing than are cars.

- Cars are more likely to use the shoulder when passing homes on roadways with 11-foot lanes than on those with 12-foot wide lanes. In general, vehicles were more likely to use the shoulder when passing 16-foot wide homes than 14-foot wide homes independent of lane width. Insufficient data exist to determine if the use of shoulders for trucks follows the same pattern.

- Shoulder use of cars passing homes increases as the shoulder conditions improve. In general, vehicles were more likely to use the shoulder when passing 16-foot wide homes than 14-foot wide homes for all shoulder conditions. Insufficient data exist to determine if the use of shoulders for trucks follows the same pattern.

- Both cars and trucks were more likely to travel on the shoulder when approaching homes on two-lane undivided roadways (in the oncoming direction) than when passing on multilane divided highways (travelling in the same direction). Trucks were more likely than cars to use the shoulder when passing on both road types. In general, vehicles were more likely to use the shoulder when passing 16-foot wide homes than 14-foot wide homes when travelling on either multilane divided or two-lane undivided roadways.

- The results indicating increased shoulder use by vehicles passing tractor/home combinations suggest that the safety of these passing vehicles is likely degraded. This safety degradation is based on the fact that passing vehicles are more likely to use the shoulders, thus reducing the margin of error available to the passing vehicles. In addition, shoulder surface conditions are generally poorer than surface conditions of the normal travel lanes and can lead to increased control difficulty for the passing vehicles.

- It may sometimes be argued that because there is a lack of accident data demonstrating a clear relationship between manufactured home transport and accident experience that there is no safety degradation resulting from the movement of homes. This is not necessarily true if accidents, or near-accidents, involving vehicles in the vicinity of home units do occur and are indirectly influenced by their presence (e.g., traffic congestion, visibility restrictions, etc.). Degradation in safety margins can still occur even if it does not lead to specific, measurable, and well defined crash events that are ultimately recorded in the accident record.

The low-speed turning analyses described in Section 4 indicate that:

- Both 14-ft, 16-ft wide, and 18-ft wide tractor/home units require considerably greater turning width at intersections (an additional 9 feet or more) than many other highway vehicles —including several types of large combination vehicles (doubles and triples). 14-ft wide by 80-ft long home units require approximately 35 feet of swept path width in turning through a normal right-hand intersection; 16-ft wide homes require 37 feet; and 18-ft wide units about 39 feet .

- Mobile home *width* is nearly as important a factor as *length* in contributing to the amount of space required by such vehicles when turning at intersections. Approximately half of the required turning space is due to the length of such vehicles; the other half of required turning space is attributable to their width.

- Curb clearance levels at turning intersections are diminished by approximately three feet when the home width is increased from 14-ft to 16-ft, and diminished by approximately six feet when the home width is increased from 14-ft to 18-ft.

- Minimum curb radii need to be increased approximately 7 feet for every 2 feet of additional home width in order to provide a comparable level of curb clearance.

- The more restrictive intersections likely encountered by tractor/home combinations in Michigan need to be at least 47 feet in radius for 14-ft wide homes, 53 feet in radius for 16-ft wide homes, and 60 feet in radius for 18-ft wide homes. These curb radii provide 1) minimal curb clearances while conducting 90-degree right-hand turns, and 2) avoid undesirable initial offsets by homes into oncoming traffic. (Curb radii less than these levels require tractor/home combinations to encroach, prior to the start of the turn, into oncoming traffic lanes in order to complete the turn with no curb-side conflicts.)

- Overhang or swing-out behavior exhibited by the outside rear-end of mobile homes during tight turning, as occurs at intersections, is particularly large (2 feet or more) when compared with overhang of conventional highway vehicles. A 16-foot wide home would increase this swing-out encroachment motion by an additional 1-foot margin beyond that seen for a 14-foot wide home; an 18-ft wide would increase this encroachment motion by an additional 2 feet over 14-ft wide homes.

- Encroachments into oncoming (or opposing) traffic lanes is the primary means available to tractor/home combination drivers for performing turns at more restrictive intersections (those existing intersections with smaller than required curb radii and not originally designed to accommodate vehicles of this size). The amount of required encroachment increases significantly with home width.

- A tractor/home unit that is just barely able to turn through a given intersection with minimal clearance, will require an additional 4 feet of offset (towards or into oncoming traffic lanes) in order to also turn through the same intersection with minimal clearance if its width is increased by 2 feet. This magnification, or doubling, of required space deriving from increased home width is significant, since all of the additional space required by the tractor/home combination (4 feet in this case) is obtained by offsetting the tractor/home combination towards oncoming traffic lanes. (A comparable 18-ft wide home would require an initial offset of 8 feet toward oncoming traffic lanes.)

- Most freeway exit ramps under low speed turning conditions do not provide special clearance problems for 14-ft wide and 16-ft wide tractor/home combinations. However, 18-ft wide homes will require the tractor driver to steer along an outer (larger radii) path on many ramps in order to provide additional clearance along the inner shoulder for the home. (On a 300-ft radius turning ramp, with the tractor centered in the turning lane, the wheel sets under an 80-ft long home unit will offtrack towards the inside of the curve approximately 6 feet at speeds less than 8 mph.)

The computer analyses of highway-speed conditions presented in Section 5 indicate that:

- For tractor/home combinations operating at speeds of 45 mph under idealized (steady and non-varying) crosswinds of 25 mph, the rear-end of 80-ft long home units will offtrack laterally about 1 foot. These results are largely independent of width, though wider (and thereby heavier) home units do exhibit approximately 5% less offtracking (0.5 inches) per 2 feet of additional home width under these conditions.

- The same analyses indicate that when realistic crosswind profiles that include natural, random-like variations are accounted for as well, the level of peak lateral offtracking exhibited by the same set of tractor/home combinations increases from 1 foot to approximately 1.5 feet.

- Increasing vehicle speed from 45 mph to 55 mph (22%) increases the crosswind offtracking amount by an additional 13%.

- Home units that are 20% lighter than the average home unit examined here, will also show increases of 20% in crosswind offtracking levels.

- The random-like and variable component of natural crosswinds is an important characteristic that acts as an on-going excitation of the tractor/home combination system and that acts to amplify lateral space demands (versus more idealized, non-varying crosswind disturbances).

- The influence of most highway cross-slopes on offtracking of tractor/home combinations while travelling in a straight-line direction is small and largely independent of width. A highway having a 2% cross-slope induces about 0.22 feet of offtracking at the end of an 80-ft long home unit.

- Superelevated highway curves (freeway connectors with operating speeds of 45-55 mph), require less than a foot of additional lateral space to accommodate tractor/home combination offtracking tendencies along such curves. (Along a 1270-ft radius curve with 6.7% superelevation, the wheel sets under an 80-ft long home unit will offtrack towards the inside of the curve nearly 1 foot at a speed of 45 mph, and approximately 0.5 feet at a speed of 55 mph.)

The braking performance and hitch load analyses seen in Section 6 indicate that:

- The braking capabilities of most tractor/home combinations are dependent primarily upon the towing tractor for stopping power. Since the tractor unit constitutes only 35% or so of the total combination vehicle weight, the braking ability of such vehicles is notably poor. Consequently, a strong disparity exists between the stopping capability of tractor/home combinations and most other highway vehicles.

- From speeds of 45 mph on dry high-friction pavements, approximately 200 feet of stopping distance is required for tractor/home combinations. Passenger cars typically require half this stopping distance from the same speed. Heavy trucks require about two-thirds this distance.

- From speeds of 55 mph on dry pavement, more than 300 feet of stopping distance is required for tractor/home combinations. Again, passenger cars typically require less than half this stopping distance and heavy trucks about two-thirds this distance.

- Slightly longer stopping distances are required for wider homes because of their increased weight.

- Over-braking by the tractor driver (inadvertent or emergency-induced) will typically result in an unstable jackknife response. This undesirable tendency further reduces the margin for error and controllability for the tractor driver during braking conditions.

- Tractor/home oscillatory behavior (or sway) at highway speeds is very sensitive to the hitch load percentage (percentage of home weight carried by the tractor at the hitch location). A normal or design value of 24% provides good damping and prevents unwanted oscillatory behavior. Reducing the hitch load percentage to a level of 12% can produce unstable oscillatory responses. Hitch load percentages in the vicinity of 18% produce moderate amounts of oscillatory behavior.

- Increasing vehicle speeds from 45 mph to 55 mph results in less system damping and increases the likelihood of oscillatory behavior, particularly when hitch load percentages fall below 20%.

- Wider and longer home units exhibit slightly less damping (or slightly greater oscillatory behavior) than shorter and narrower home units for the same speed conditions and hitch load percentages.

- Housing manufacturer design guidelines (described at the end of Section 2) are reasonable rules to follow in providing for adequate hitch load percentages and the number of axles on home units. The "2/3 rule" regarding axle locations results in a 24% hitch load percentage, provided the home unit has its weight uniformly distributed along its length.

— • — *Recommendations* — • —

The following recommendations, in general, identify tractor/home combinations operating along two-lane undivided highways as the primary focus of concern. The concern is especially magnified along such routes that have narrow and/or deteriorating shoulders, particularly for oversize homes wider than 14 feet. This scenario frequently results in tractor/home units encroaching across undivided highway centerlines into oncoming traffic lanes. This is not normally viewed as a reasonable method of ordinary transport practice for highway vehicles. Consequently, current transport of 16-ft wide homes along two-lane highways with particularly narrow shoulder widths is not supported by this study until shoulder width upgrades along these highway sections are undertaken. An interim/transitional period of operation for 16-ft wide homes is suggested as a possible temporary solution for permitting 16-ft wide transports to continue to operate during any shoulder reconstruction period. The study does not support a status quo position that permits continued indefinite access by oversize 16-ft wide homes to those two-lane undivided highways having limited width capacities.

In general, divided multilane freeway operations in rural, low traffic density areas with wide shoulders do not present a significant problem for transporting 14-ft or 16-ft wide homes. However, these same vehicles must ultimately access narrower secondary roadways. In doing so, their mobility is restricted and their presence reduces the normally accepted vehicle-to-vehicle spacing expected by other highway users. Accordingly, the aforementioned concerns regarding tractor/home combinations operating along two-lane undivided highways will still frequently apply in many cases.

The specific recommendations based upon the findings and observations of this study are that:

Highway Shoulder Upgrades

- If the State determines that it is in its interest to allow the movement of 16-ft wide homes over the highway, paved shoulder widths along two-lane undivided highways likely to be used by tractor/home combinations in Michigan, and not currently meeting recommended minimum widths (indicated below), should be upgraded to those recommended widths. In addition, gravel areas adjoining those paved shoulders should meet comparable width requirements to provide sufficient clearance for lateral overhang of the home. This recommendation is based upon consideration of cumulative lateral space requirements that account for home width, crosswind influences, highway cross-slope effects, driver steering uncertainties, and minimal buffer zones of 1 foot along both sides of the home unit, such that home encroachments across highway centerlines and into oncoming traffic lanes are avoided.

— For home widths of 14 feet, the minimum cleared width (consisting of the travel lane, the paved shoulder width, and the adjoining gravel width) should be at least 18 feet of which the total paved surface portion (travel lane and paved shoulder area) is at least 16 feet.

— For home widths of 16 feet, the minimum cleared width should be at least 20 feet of which the total paved surface portion (travel lane and paved shoulder area) is at least 17 feet.

— For home widths of 18 feet, the minimum cleared width should be at least 22 feet of which the total paved surface portion (travel lane and paved shoulder area) is at least 18 feet. (If the wheel track for 18-ft wide homes exceeds 9' 6", an additional 1 foot of shoulder pavement is recommended.)

These recommended minimum paved surface widths (lane + shoulder) suggest that for two-lane highways with lane widths of 12 feet, the paved shoulder should be at least 4 feet wide to accommodate 14-ft wide homes, 5 feet wide to accommodate 16-ft wide homes, and 6 feet wide to accommodate 18-ft wide homes. (Eleven-foot wide travel lanes would increase these recommended paved shoulder widths by 1 foot.)

[These recommendations are based upon a simple formula for estimating the minimum cleared width (i.e., travel lane, paved shoulder, and additional gravel width) given by, $C = W + 4.25$, where W is the width of the home unit and C is the minimum cleared width. The 4.25 (feet) value is used to account for the combined effects of crosswind influences (1.5 feet), highway cross-slopes (0.25 feet), normal driver steering uncertainty (at least 0.5 feet), and 1 foot buffer margins along both sides of the home unit (2 feet).]

- The recommended upgrades do affect shoulder design and strength issues. Such upgrades would need to strengthen affected shoulder areas (by increasing pavement depths) in order to handle the increased loads regularly being carried along such routes.

- For those two-lane highway segments requiring shoulder widening, a transitional time period will exist prior to completion of the recommended shoulder widening construction. During this transitional period, an additional lead escort vehicle (preferably from a police agency) should be provided at these specific route sections to slow down and warn oncoming traffic of likely encroachments across the centerline by the home unit.

- Use of an additional lead escort vehicle (police or otherwise), itself, in lieu of the accompanying shoulder widening effort recommended above, is not suggested as an alternate long term solution along such routes, particularly for homes wider than 14 feet. Such escort activities by police agencies are only being identified as one possible method for improving the safety along such routes under a well defined short-term arrangement.

Highway Intersections

- Curb radii at intersection turns along routes of tractor/home combinations should generally be increased to at least 60 feet to provide sufficient curb clearance and avoidance of encroachments by home units into oncoming traffic lanes at the start of intersection turning maneuvers. Design values for specific intersection geometries could be based upon the information contained in Section 4.

- Traffic control and stoppage is recommended for those restricted intersections that require encroachments by home units into oncoming traffic lanes from their initial turning position. Cross-road traffic will always be stopped and cleared in any event to allow the tractor/home to complete its turn into the lanes of oncoming cross traffic. However, additional assistance is likely required at many restricted intersections in order to not only control the cross-road traffic, but to stop and control the following and opposing traffic as well at the start of intersection turns. Traffic control under these circumstances should be exercised by an agency having the proper authority.

Tractor/Home Braking Performance

- Addition of brakes to all axles (as opposed to one or two) on the home unit is strongly recommended to improve the braking performance of most tractor/home combinations. This will also help to alleviate the braking demand upon the tractor unit and help to better stabilize the combination vehicle during emergency stops. Jackknifing tendencies will likewise be reduced. This raises the question of how to best accomplish this because of existing federal regulations and/or interstate commerce issues.

- Because of the limited stopping capability of existing tractor/home combinations and their tendency to jackknife under emergency braking, sufficient space should be provided between the lead escort vehicle and the towing tractor. This lead buffer zone should be maintained free of traffic with highly visible signing located on the back of the lead escort vehicle and the front of the tractor to warn adjacent vehicles out of this zone. For freeway travel at speeds of 45 mph, the length of this buffer zone should be at least 250 feet. At lower speeds of 25 mph, the buffer zone should be maintained clear of traffic for a distance of 150 feet. (These recommended clearance distances reflect a perception and reaction time of 2.5 seconds for the tractor driver and the stopping ability of tractor/home combinations relative to passenger cars.)

- The lead escort vehicle, in cooperation with the tractor driver, should maintain reasonable lead distances ahead of the tractor/home combination so as to discourage other traffic from wandering into the lead buffer zone. Lead distances should not exceed 500 feet on the freeway and 200 feet along slower 25 mph routes having additional traffic.

- Slippery surface conditions further aggravate the braking capabilities of tractor/home combinations and travel should not be allowed during snow/ice conditions.

Speed Limits and Enforcement

- Because of the limited stopping ability of tractor/home combinations, maximum speeds for such vehicles should be limited to 45 mph on freeways. (At freeway speeds of 55 mph, the recommended buffer zone would have to grow to a distance of nearly 400 feet and could not be easily maintained free of other traffic by the lead escort vehicle.) On two-lane undivided highways, where sight distances are limited and travel conditions are less ideal, the current speed limit of 35 mph should be maintained.

- Enhanced enforcement of speed limits for tractor/home combinations is recommended. Field observations of average tractor/home combination travel speeds in this study indicated routine violation of allowed limits on their permits. Based upon the braking performance disparities that exist between tractor/home combinations and other highway vehicles, more vigorous enforcement of speeding is recommended. Computer-based analyses also indicate that greater oscillatory behavior and considerably greater stopping distances are exhibited by these vehicles as speeds increase. Responsibility for safe operation of the units rests largely on the tractor operators and their employers. Speed regulation possibilities to consider by companies or individuals responsible for shipping these homes could include: A) installing automated data recorders on all tractors used to ship homes with the data from these recorders being sent to MDOT to ensure compliance, or B) providing an equivalent method to guarantee compliance. MDOT should be empowered to withhold shipping permits from those companies or individuals that have an excessive record of speed limit violation.

Tractor/Home Transport Practice

- Design practice for home units that result in approximately a 24% hitch load percentage is supported. The axle placement rule noted in Volume 2 that locates the axle-set centerline two-thirds behind the front of the home is an example. In all cases, hitch load percentages should be maintained in the 20% to 30% range. Side-to-side (sway) oscillations begin to develop in tractor/home combinations when hitch load percentages fall below the 20% level, thereby requiring additional lateral space and increasing the chances of lateral encroachments.

- The 6000 lb per axle (maximum) rule for determining the number of axles to use on home units, also described in Section 2, is likewise supported and recommended.

Existing Permit Practice

- Existing permit rules regarding time of day restrictions, urban area restrictions, escort practices, seasonal restrictions, and designated routing by knowledgeable state authorities is supported.

- A uniform height limitation on home units (e.g., 13' 6" , or, some equivalent) number should be determined based upon a survey of bridge height clearances and similar limitations along the routes designated for all tractor/home combinations.

Bridge Crossings

- Traffic control and stoppage is recommended at bridge crossings having widths less than 30 feet for 14-ft wide homes, 34 feet for 16-ft wide homes, and 38 feet for 18-ft wide homes.

Escort Vehicles and Driver Training

- Given the longer stopping distances required by tractor/home units, it is important that escort vehicles work in close cooperation with the tractor/home units to control traffic travelling in close proximity to the homes. The role escort vehicles play in traffic control is critical such that specific, detailed, and approved training programs should be developed and enforced for any and all drivers of tractor/home escorts. Of critical importance in this training is the need to ensure that a clear lane of movement is available to the tractor/home unit for any lane change or other maneuvers that involve the tractor/home unit changing direction or speed. It is also important that escort vehicle drivers be advised of the dangers associated with both leading the tractor/home unit too closely or allowing other vehicles to get between the front of the tractor/home unit and the lead escort. The tractor/home unit requires longer distances to stop and complete other maneuvers, and it is the role of the escorts to assure that proper distances are maintained between the tractor/home unit and other vehicles. Escort training programs may be able to be "piggy-backed" onto existing specialized driving courses. Such piggy-backing would reduce costs of training and may in fact enhance more general knowledge and skills of escort team drivers to maximize their ability to escort manufactured housing units. To ensure escort drivers do complete authorized courses, it is recommended that escort drivers be certified through some official process and that only certified drivers be permitted to escort home units.

  It is probably true that proper escort vehicle behavior may frustrate the inexperienced and generally uninformed public, especially because proper escort behavior may involve impeding the planned passing behavior of other vehicles. However, this frustration may be mitigated by a thorough public information and education program to inform the general driving public about the dangers associated with improper passing, following, and lead distances when driving around the tractor/home units.

Public Information & Education Programs

- Because the general driving public is likely unaware of the maneuvering limitations of tractor/home units and the importance of maintaining a safe following, leading, and passing distance when travelling near these vehicles, a comprehensive PI&E effort is recommended. This PI&E effort should be concentrated during the beginning of peak delivery periods, but should continue throughout periods when tractor/home units are travelling on the roadways.

- A comprehensive PI&E strategy involving all media (print and broadcast) should be employed to reach the broadest possible audience in those areas most affected by home shipments. This may include special educational posters at rest areas, developing informational articles for newspapers to print periodically, developing public service announcements for radio and television, and other forms of media. These PI&E materials should stress that it is as important, if not more so, for the general driving public to drive carefully and cautiously around tractor/home units than for the tractor/home unit drivers. A special emphasis of the PI&E campaign should be to instruct drivers not to try to "beat" the escort vehicles. The escorts are there to protect the area around the tractor/home unit to ensure safe transportation for both the home and those driving in the proximity of the home. This special emphasis should also stress the importance of not getting between the escort vehicles and the tractor/home unit. This is especially true for vehicles that may want to duck between the tractor/home unit and the lead escort vehicle. This area (between the tractor/home unit and lead escort) is there as a buffer zone providing the tractor/home unit additional space in which to complete stops safely.

Urban Freeways and Multilane Undivided Highways

- Although this study did not gather much data along urban freeways and multilane undivided highways, it was apparent that under such congested traffic conditions, tractor/home combinations introduce more complicated traffic situations and potential for conflicts. Accordingly, the study recommends continued support of existing geographical and time-of-day restrictions on tractor/home combinations along urban freeways and multilane highways.

- Along more rural multilane undivided highways, shoulder quality and width seemed to vary to a much greater extent than on interstate freeways. Under these travel conditions, encroachments by the home into the passing lane are likely to be more frequent. Consequently, greater vigilance and control of surrounding traffic by the escort vehicles should be emphasized under these circumstances.

References

1. 12-Foot Wide Mobile and Modular Home Transit Study on the State Trunkline System, TSD-RD-206-72, Standards and Development Unit, R & D Section, Traffic and Safety Division, Michigan Department of State Highways, 1972.

2. 14-Foot Wide Mobile and Modular Home Transit Study, TSD-G-188-71, Standards Unit, Geometrics Section, Traffic and Safety Division, Michigan Department of State Highways, 1971.

3. Sufficiency Rating, Michigan State Trunkline Highways, Michigan Department of Transportation, Bureau of Transportation Planning, 1990.

4. MacAdam, C.C. et al., "A Computerized Model for Simulating the Braking and Steering Dynamics of Heavy Trucks, Tractor-Semitrailers, Doubles, and Triples Combinations, Users' Manual--PHASE 4" (co-author). HSRI, Univ. of Mich., Rept. No. UM-HSRI-80-58, September 1980.

5. MacAdam, C.C., "The Crosswind Sensitivity of Unladen Doubles and Triples Combinations and their Susceptibility to Wind-Induced Offtracking and Rollover," *Proceedings of the 12th IAVSD Symposium on the Dynamics of Vehicles on Roads and Tracks*, Lyon, August 1991.

Related Bibliography.

Zeeger, C.V. et al, "Safety of Wide Trucks on Narrow Roadways," Contract No. DTFH61-87-Z-00077, Final Report, 1990.

Decabooter, P.H. and Solberg, P.E., "Operational Considerations Relating to Long Trucks in Urban Areas," Paper No. 880071, 68th Annual Meeting, TRB, 1989.

"A Policy on Geometric Design of Highways and Streets - 1990", Washington D.C., AASHTO, 1990.

Appendix A. Videotape Samples of Tractor/Home Observations.

Sample of videotape scenes from the field study.

Figure A.1. 16-foot wide home passing a 14-foot wide home.

Figure A.2. 14-foot wide home passing a 12-foot wide home.

Figure A.3. 16-foot wide home passing an automobile.

Figure A.4. Truck off of paved shoulder while passing a 16-foot wide home.

Figure A.5. 14-foot wide home on the exit ramp from Temp. I-69 North to I-96 West.

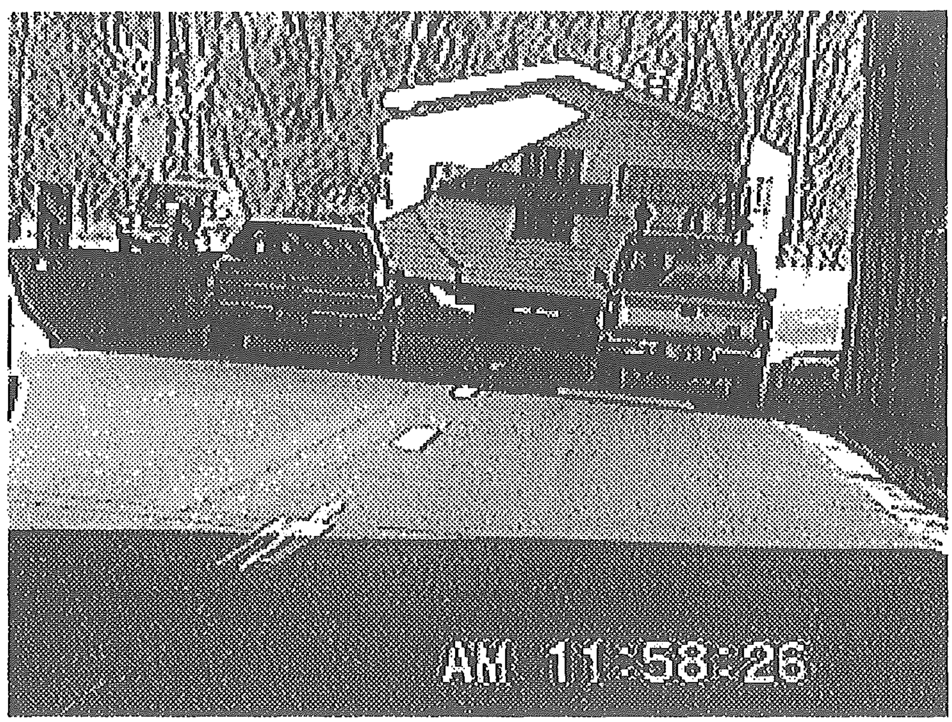


Figure A.6. 16-foot wide home in a construction zone on Temp. I-69 North.

Figure A.7. Queue of passenger vehicles passing a 16-foot wide home.

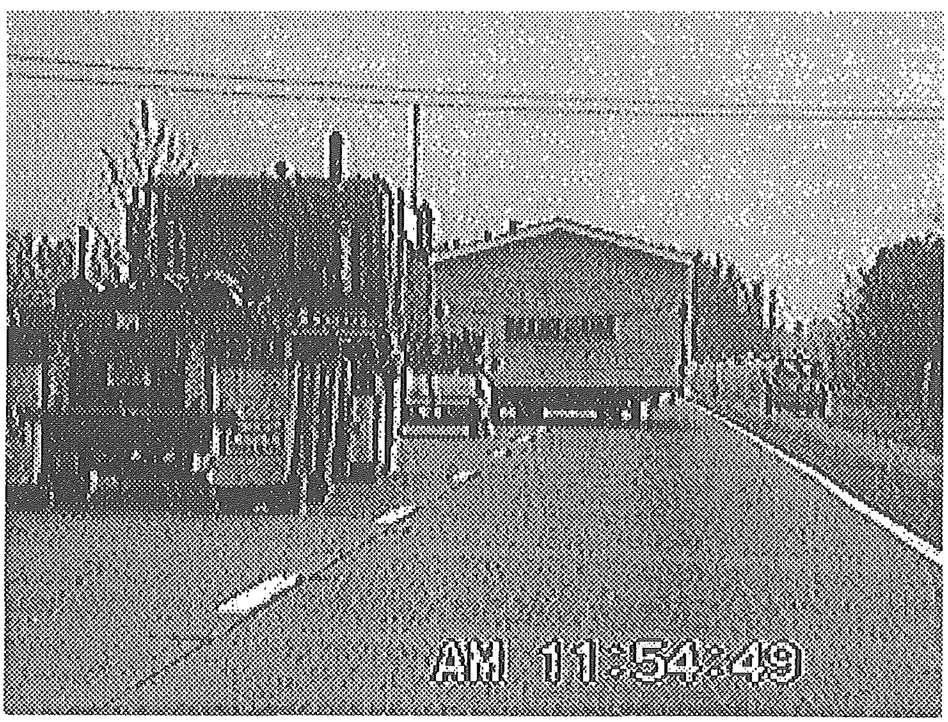


Figure A.8. 16-foot wide home moves to the left lane to avoid a vehicle on the right shoulder.

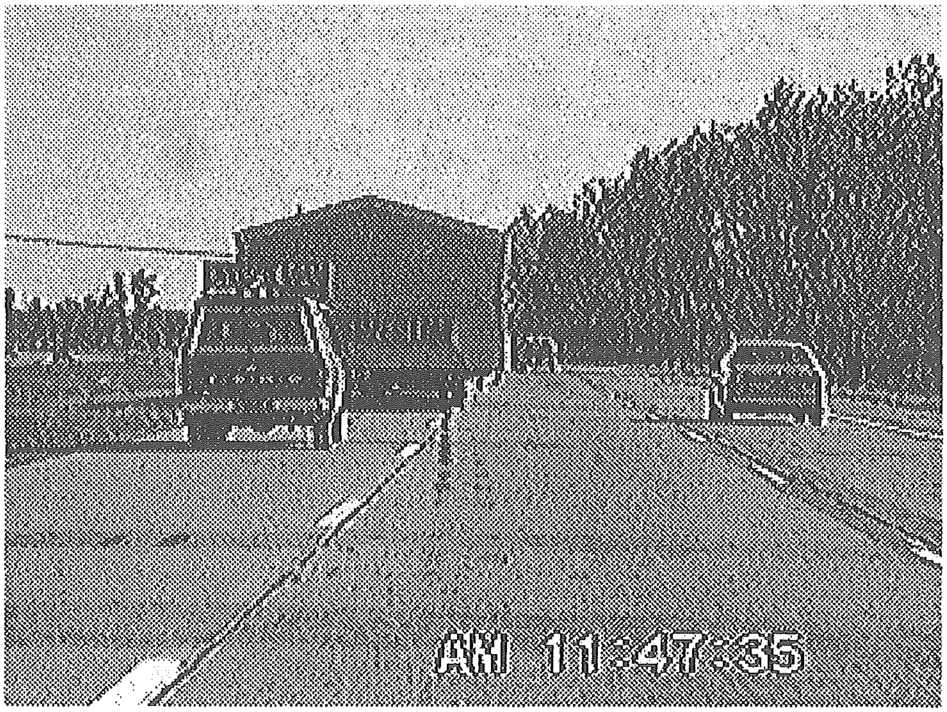


Figure A.9. 16-foot wide home moves to the left lane to allow room for a passenger car to enter the highway.

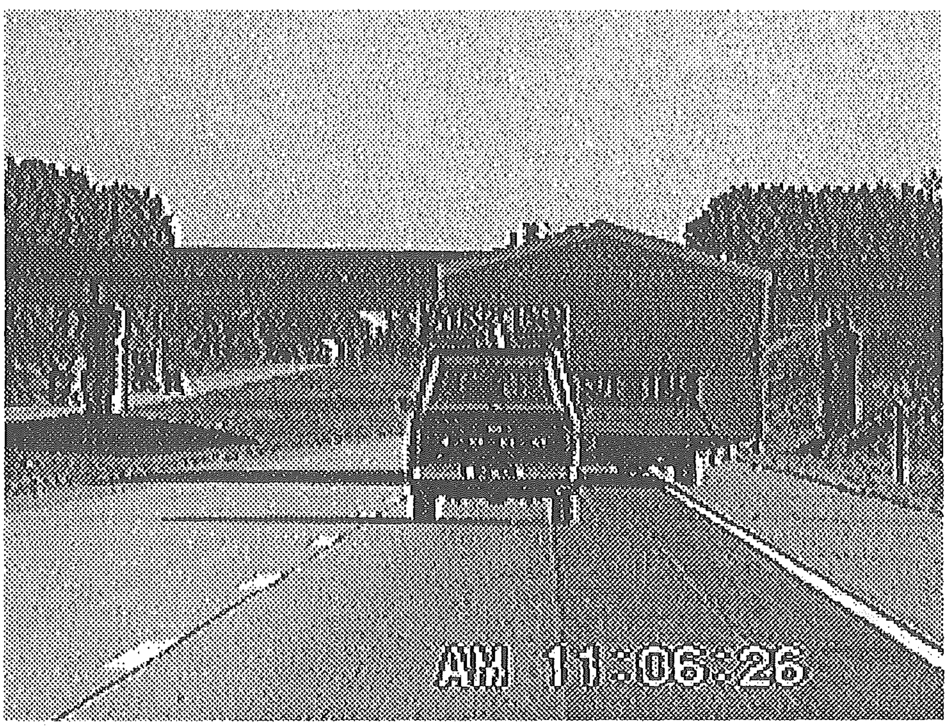


Figure A.10. 16-foot wide home on I-69 East of Lansing with a wide shoulder and no traffic present.

Figure A.11. 16-foot wide home on a busy 3-lane highway (I-94 East).

Figure A.12. 16-foot wide home and escort vehicle occupy rightmost 2 lanes of a 3-lane highway.

Figure A.13. 16-foot wide home in a low traffic density area on I-75 North, south of Grayling.

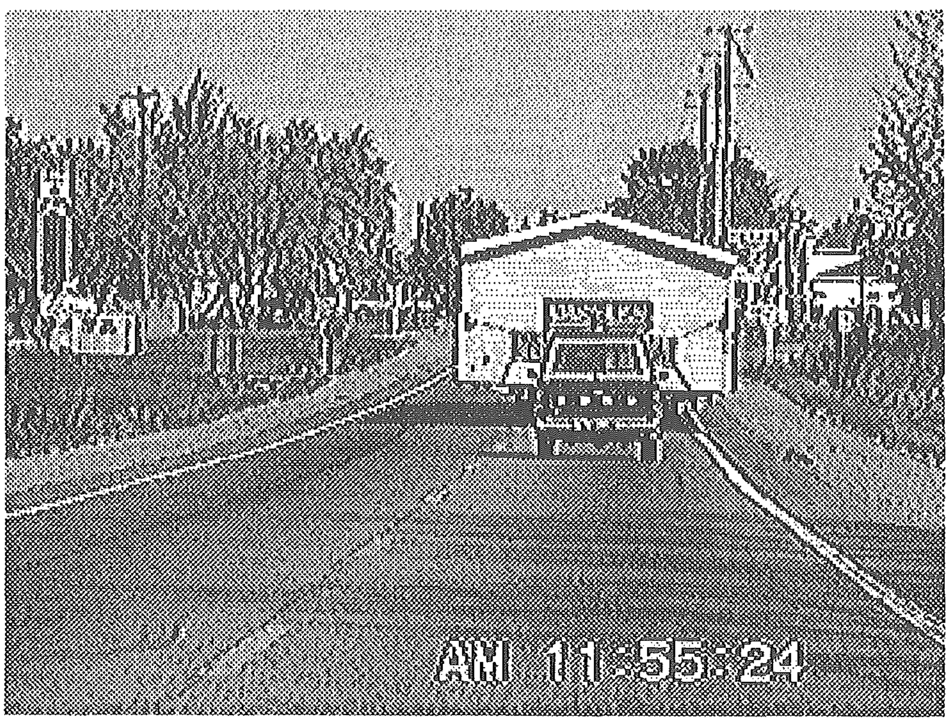


Figure A.14. 16-foot wide home encroaches across the centerline on a 2-lane undivided highway.

Figure A.15. 16-foot wide home encroaches across centerline on a 2-lane undivided highway.

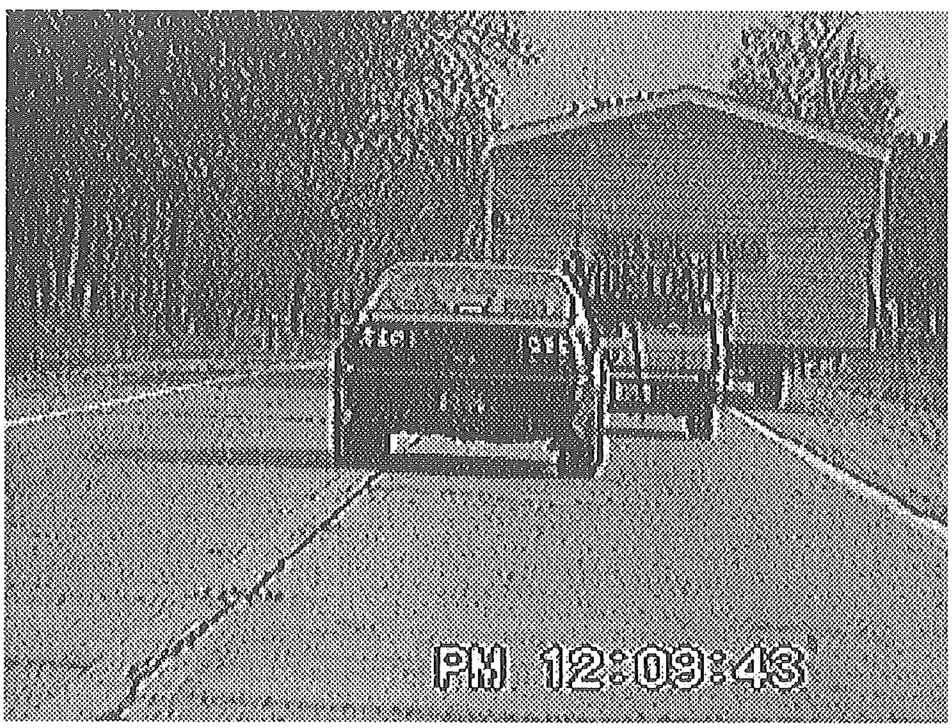


Figure A.16. Passenger vehicle behind a 16-foot wide home preparing to pass.

Figure A.17. Passenger car passing a 16-foot wide home in the on-coming traffic lane.

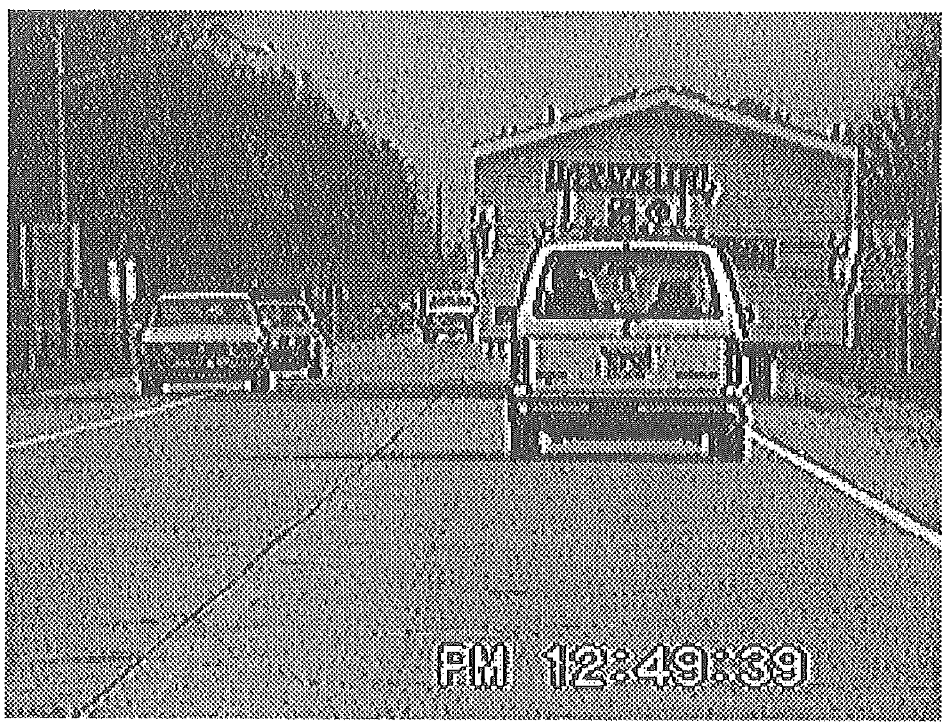


Figure A.18. On-coming traffic on the shoulder.

Figure A.19. Home wheels off right shoulder and on to gravel.

Figure A.20. 16-foot wide home travelling through a small town.

Figure A.21. On-coming tractor-semitrailer utilizing the shoulder.

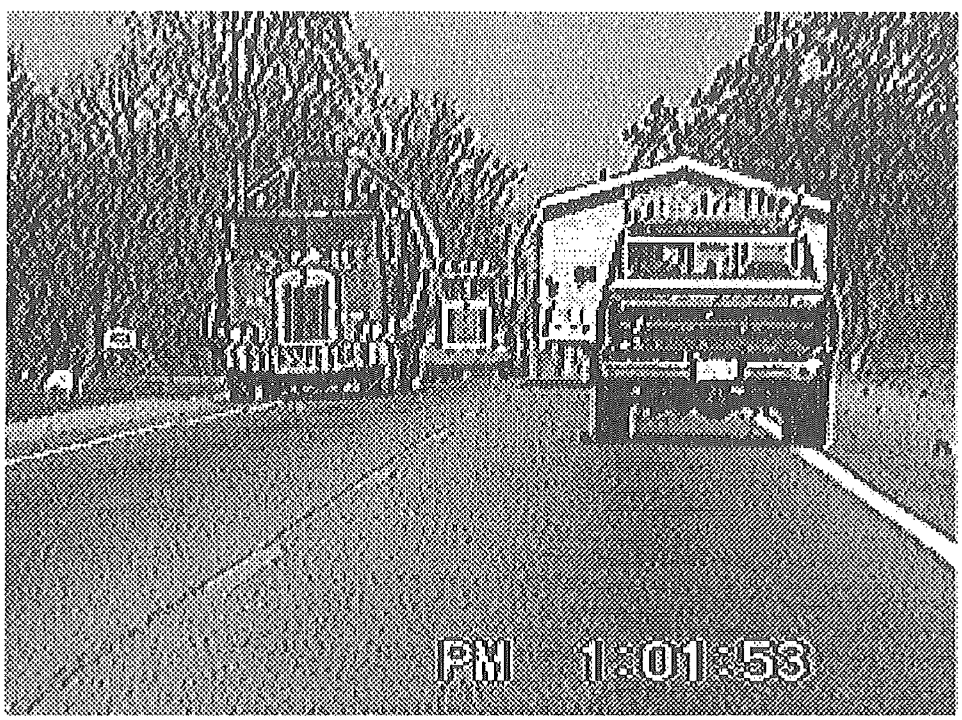
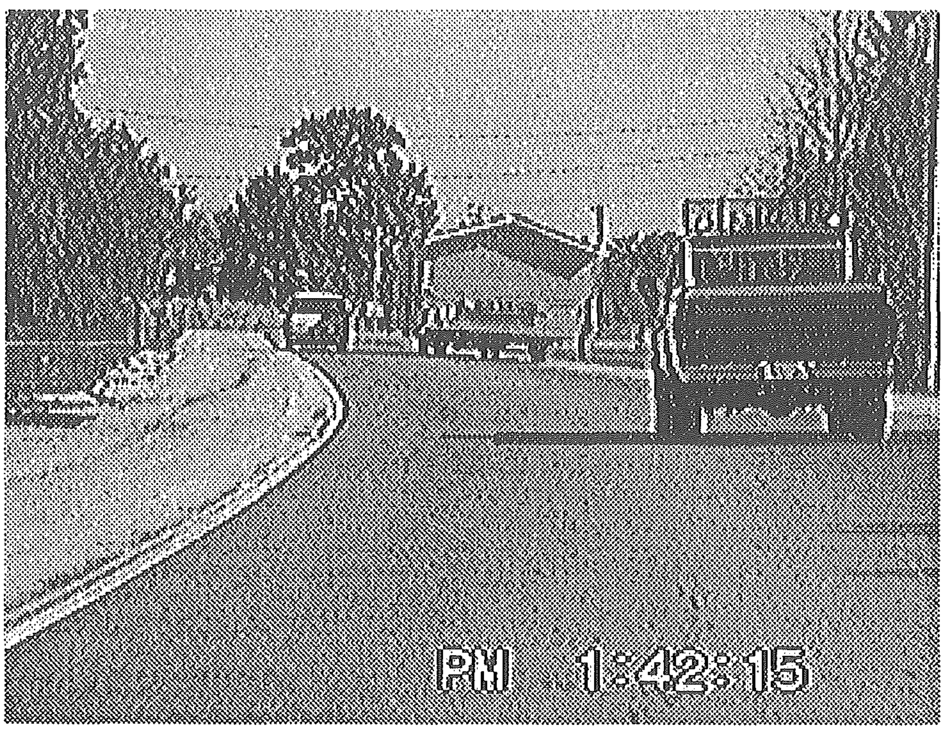


Figure A.22. On-coming tractor-semitrailer utilizing the shoulder.

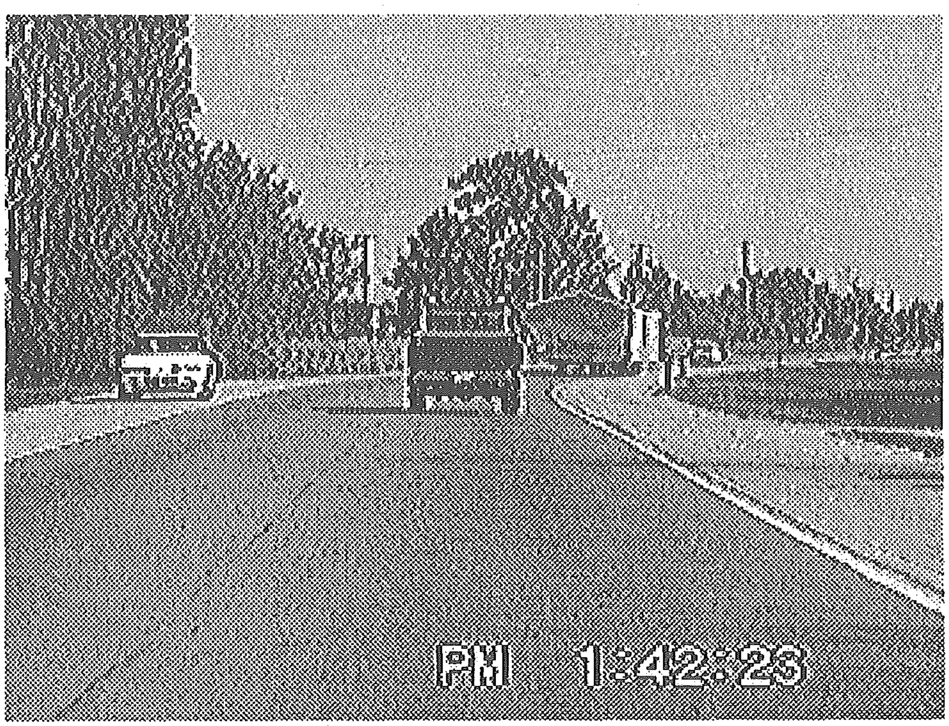
(a). Passenger car begins to pass.



(b). Passenger car beside a home in the on-coming lane.

Figure A.23. On-coming passenger car forced on to the shoulder to avoid the passenger car overtaking the home.

(c). On-coming passenger car moves on to the shoulder.



(d). On-coming passenger car still on the shoulder.

Figure A.23. On-coming passenger car forced on to the shoulder to avoid the passenger car overtaking the home.

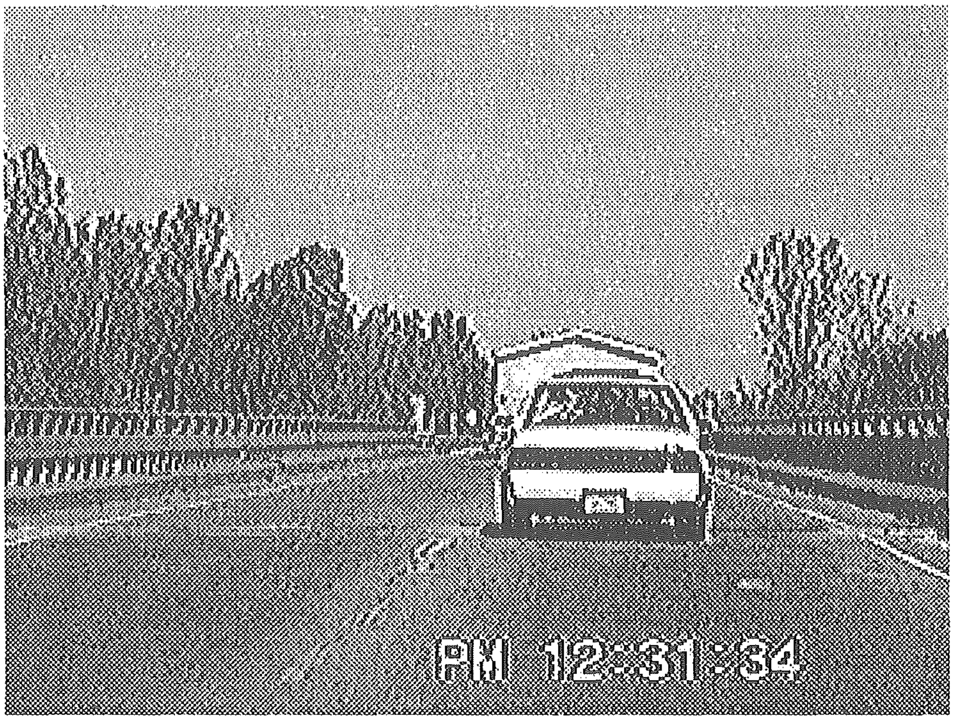
(a). On-coming passenger vehicle begins to turn in front of home.

(b). Tractor over-brakes and locks its wheels to avoid the turning vehicle.

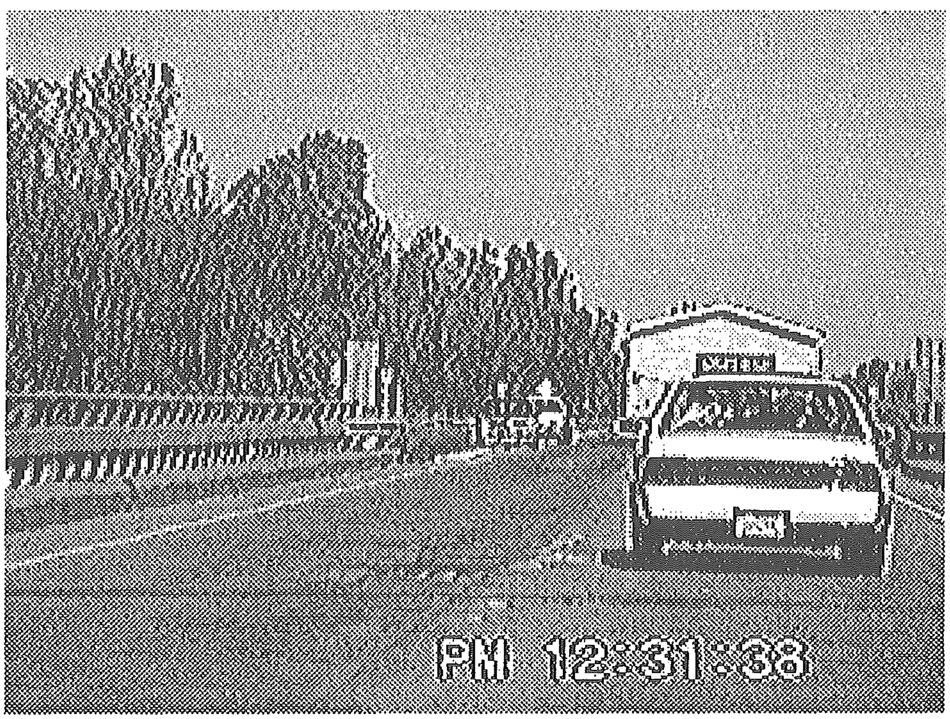
Figure A.24. Towing tractor locks its wheels to avoid an accident.

(c). Tractor/home combination recovers.

Figure A.24. Towing tractor locks its wheels to avoid an accident.

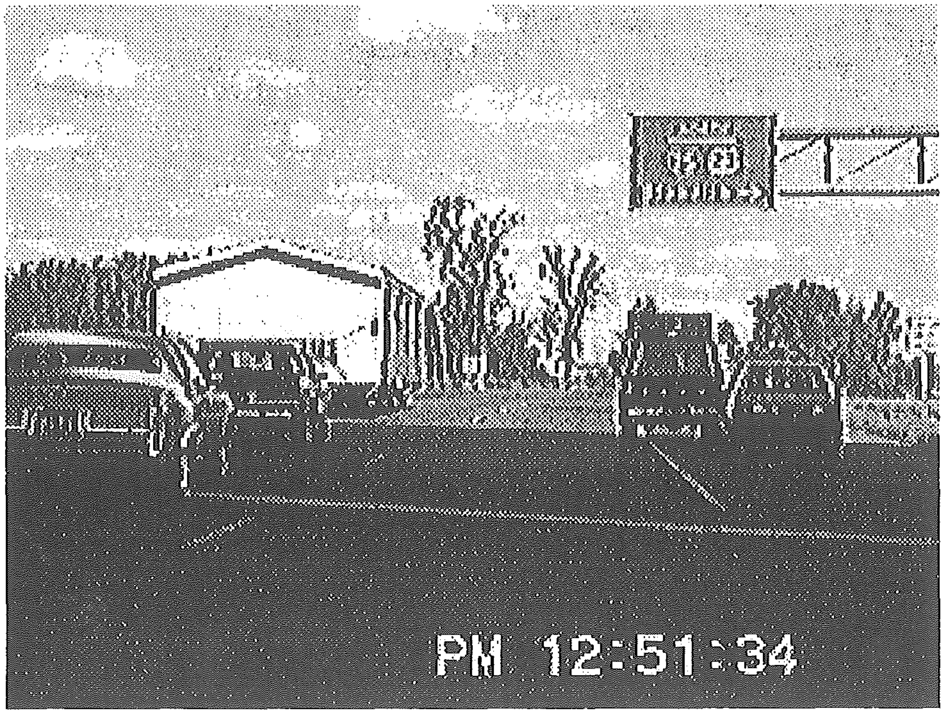


(a). Home crossing the bridge.



(b). On-coming traffic waiting to cross as the home exits the bridge.

Figure A.25. 16-foot wide home crossing a bridge on a 2-lane undivided road.

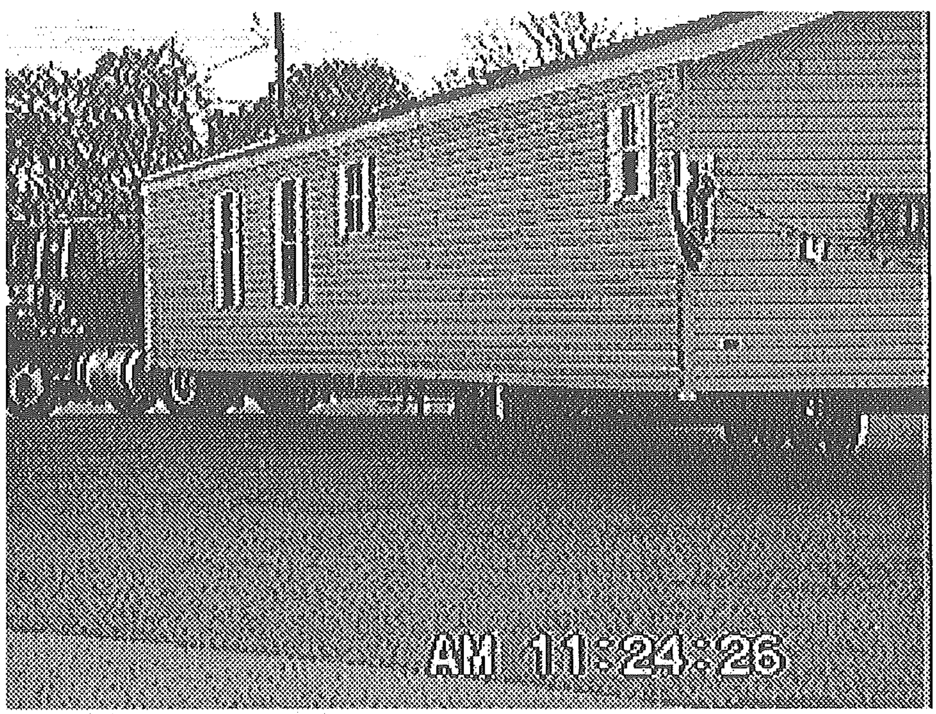


(a). Passenger vehicles backed up behind a home preparing to turn.

(b). Home starts its turn.

Figure A.26. 16-foot wide home exits M-13 North to a highway.

(a). Typical two-axle tractor hauling a 16-ft wide home.



(b). Rear view.

Figure A.27. 16-foot wide home & towing tractor.

Appendix B. Baseline Vehicle Parameters Used in Computer Analyses.

A listing of the parameter "echo" from the UMTRI Phase 4 computer model is provided in this Appendix for the 16-ft wide baseline tractor/home combination.

Tractor / Mobile Home / 45K gross; 25 mph Crosswind; 45 mph Vehicle Speed.

0 SIMULATION OPERATION PARAMETERS:

```
0       VEHICLE CONFIGURATION (NUMBER OF TRAILERS - ENTER 0 FOR A STRAIGHT TRUCK)                        1
        INITIAL VELOCITY (FT/SEC)                                                                    66.00
        STEER TABLE (NUMBER OF LINES):  POSITIVE -STEER ANGLE TABLE, NEGATIVE - PATH FOLLOWER TABLE        -4
0                 CLOSED-LOOP PATH FOLLOWING MODE
0                 X-Y PATH COORDINATES :
0                                                                              X          Y

0                                                                           (FEET)     (FEET)
                                                                               .00        .00
                                                                            100.00        .00
                                                                            150.00        .00
                                                                           9999.00        .00

                  DRIVER TRANSPORT LAG (SEC) :              .25
                  END OF PREVIEW INTERVAL (SEC) :          1.50

0       TREADLE PRESSURE TABLE (NUMBER OF LINES)                                                         3
             TABLE ENTRIES:                                                   TIME (SEC)    PRESSURE (PSI)
                                                                              ----------    --------------
                                                                                  .00             .00
                                                                                  .50           -8.00
                                                                                 9.90           -8.00

        MAXIMUM SIMULATION TIME (SEC)                                                                 8.01
        TIME INCREMENT OF OUTPUT (SEC)                                                                 .10
0       ROAD KEY =  0 : FLAT ROAD.
0       OUTPUT PAGE OPTION KEYS:  0 DELETES PAGES
```

SPRUNG MASS POSITION	SPRUNG MASS VELOCITY	SPRUNG MASS ACCELERATION	TIRE FORCES PAGES	BRAKE SUMMARY PAGES	LATERAL PAGES	UNSPRUNG MASS PAGES	TEMP PAGES
1	1	1	1	0	1	1	0

Tractor / Mobile Home / 45K gross; 25 mph Crosswind; 45 mph Vehicle Speed.

0 TRACTOR PARAMETERS

WHEELBASE - DISTANCE FROM FRONT AXLE TO CENTER OF REAR SUSPENSION (IN)	120.00
BASE VEHICLE CURB WEIGHT ON FRONT SUSPENSION (LB)	9500.00
BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)	7000.00
SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)	44.00
SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	15000.00
SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)	75000.00
SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)	75000.00
PAYLOAD WEIGHT (LB)	.00
*** ZERO ENTRY INDICATES NO PAYLOAD ***	
*** FIVE PAYLOAD DESCRIPTION PARAMETERS ARE NOT ENTERED ***	
FIFTH WHEEL LOCATION (IN. AHEAD OF REAR SUSP. CENTER)	-42.00
FIFTH WHEEL HEIGHT ABOVE GROUND (IN)	24.00
TRACTOR FRAME STIFFNESS (IN-LB/DEG)	.00
TRACTOR FRAME TORSIONAL AXIS HEIGHT ABOVE GROUND (IN)	36.00

0 TRACTOR FRONT SUSPENSION AND AXLE PARAMETERS

	LEFT SIDE	RIGHT SIDE
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)	-119.00	-119.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***		
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***		
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)	.00	.00
COULOMB FRICTION (LB/SIDE/AXLE)	.00	.00

AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	3719.00
ROLL CENTER HEIGHT (IN. ABOVE GROUND)	23.00
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)	.00
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)	1500.00
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)	32.00
TRACK WIDTH (IN)	80.00
UNSPRUNG WEIGHT (LB)	1200.00
STEERING GEAR RATIO (DEG STEERING WHEEL/DEG ROAD WHEEL)	28.00
STEERING STIFFNESS (IN-LB/DEG)	11000.00
TIE ROD STIFFNESS (IN-LB/DEG)	11000.00
MECHANICAL TRAIL (IN)	1.00
TORSIONAL WRAP-UP STIFFNESS (IN-LB/IN)	150000.00
LATERAL OFFSET OF STEERING AXIS (IN)	3.00

0 TRACTOR FRONT TIRES AND WHEELS

	LEFT SIDE	RIGHT SIDE
CORNERING STIFFNESS (LB/DEG/TIRE)	-1.00	-1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***		
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***		
LONGITUDINAL STIFFNESS (LB/SLIP/TIRE)	-2.00	-2.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***		
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***		
CAMBER STIFFNESS (LB/DEG/TIRE)	.00	.00
ALIGNING MOMENT (IN-LB/DEG/TIRE)	-1600.00	-1600.00
*** NEGATIVE ALIGNING MOMENT ENTRY ***		
*** ALIGNING MOMENT CURVE FIT PARAMETERS:	(.0000 .0000 5.0000 .8000)	(.0000 .0000 5.0000 .8000)
TIRE SPRING RATE (LB/IN/TIRE)	4500.00	4500.00
TIRE LOADED RADIUS (IN)	19.50	19.50
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)	103.00	103.00

Tractor / Mobile Home / 45K gross; 25 mph Crosswind; 45 mph Vehicle Speed.

0 TRACTOR REAR SUSPENSION AND AXLE PARAMETERS

	LEFT SIDE	RIGHT SIDE
SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM	0	
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)	-131.00	-131.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***		
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***		
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)	.00	.00
COULOMB FRICTION (LB/SIDE/AXLE)	.00	.00
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	4458.00	
ROLL CENTER HEIGHT (IN. ABOVE GROUND)	29.00	
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)	.00	
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)	5300.00	
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)	38.00	
TRACK WIDTH (IN)	72.00	
UNSPRUNG WEIGHT (LB)	2300.00	

0 TRACTOR REAR TIRES AND WHEELS

	LEFT SIDE	RIGHT SIDE
0 DUAL TIRE SEPARATION (IN)	13.00	13.00
CORNERING STIFFNESS (LB/DEG/TIRE)	-1.00	-1.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***		
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***		
LONGITUDINAL STIFFNESS (LB/SLIP/TIRE)	-2.00	-2.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***		
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***		
CAMBER STIFFNESS (LB/DEG/TIRE)	30.00	30.00
ALIGNING MOMENT (IN-LB/DEG/TIRE)	600.00	600.00
TIRE SPRING RATE (LB/IN/TIRE)	4500.00	4500.00
TIRE LOADED RADIUS (IN)	19.50	19.50
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)	115.00	115.00

1
0 TRACTOR FRONT BRAKES

	LEFT SIDE	RIGHT SIDE
0 TIME LAG (SEC)	.0500	.0500
RISE TIME (SEC)	.2500	.2500
BRAKE TORQUE (IN-LB/PSI/BRAKE)	.0000	.0000
BRAKE HYSTERESIS KEY: 0 ENTRY INDICATES BRAKE HYSTERESIS OPTION NOT IN USE ON VEHICLE TRAIN		0
BRAKE PROPORTIONING KEY: 0 ENTRY INDICATES BRAKE PROPORTIONING OPTION NOT IN USE ON VEHICLE TRAIN		0

0 TRACTOR REAR BRAKES

	LEFT SIDE	RIGHT SIDE
0 TIME LAG (SEC)	.0750	.0750
RISE TIME (SEC)	.2500	.2500
BRAKE TORQUE (IN-LB/PSI/BRAKE)	2500.0000	2500.0000

Tractor / Mobile Home / 45K gross; 25 mph Crosswind; 45 mph Vehicle Speed.

0 TRAILER NO. 1 PARAMETERS

WHEELBASE - DISTANCE FROM KINGPIN TO CENTER OFREAR SUSPENSION (IN)	679.20
BASE VEHICLE KINGPIN STATIC LOAD (LB)	6768.00
BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)	22232.00
SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)	54.00
SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	310000.00
SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)	5560000.00
SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)	5560000.00
PAYLOAD WEIGHT (LB)	.00

*** ZERO ENTRY INDICATES NO PAYLOAD ***

*** FIVE PAYLOAD DESCRIPTION PARAMETERS ARE NOT ENTERED ***

0 TRAILER NO. 1 REAR SUSPENSION AND AXLE PARAMETERS

	LEADING TANDEM AXLE			TRAILING TANDEM AXLE	
	LEFT SIDE	RIGHT SIDE		LEFT SIDE	RIGHT SIDE
SUSPENSION KEY - 0 INDICATES SINGLE AXLE, 1 INDICATES FOUR SPRING, 2 WALKING BEAM			1		
TANDEM AXLE SEPARATION (IN BETWEEN LEADING AND TRAILING AXLES)			54.00		
STATIC LOAD TRANSFER (PERCENT LOAD ON LEAD AXLE)			50.00		
DYNAMIC LOAD TRANSFER (% BRAKE TORQUE REACTED AS TANDEM AXLE LOAD TRANSFER)			.00		
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)	-121.00	-121.00		-121.00	-121.00
*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***					
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***					
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)	.00	.00		.00	.00
COULOMB FRICTION (LB/SIDE/AXLE)	.00	.00		.00	.00
AXLE ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	1100.00			1100.00	
ROLL CENTER HEIGHT (IN. ABOVE GROUND)	20.00			20.00	
ROLL STEER COEFFICIENT (DEG. STEER/DEG. ROLL)	.00			.00	
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)	.00			.00	
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)	96.00			96.00	
TRACK WIDTH (IN)	114.00			114.00	
UNSPRUNG WEIGHT (LB)	400.00			400.00	

0 TRAILER NO. 1 REAR TIRES AND WHEELS

	LEADING TANDEM AXLE		TRAILING TANDEM AXLE	
	LEFT SIDE	RIGHT SIDE	LEFT SIDE	RIGHT SIDE
0 DUAL TIRE SEPARATION (IN)	.00	.00	.00	.00
CORNERING STIFFNESS (LB/DEG/TIRE)	-201.00	-201.00	-201.00	-201.00
*** CALF LESS THAN -200. INDICATES TIRE MODEL IS BEING USED ***				
*** MODEL PARAMETERS WILL BE ECHOED FOLLOWING THE TABLE ECHOES ***				
LONGITUDINAL STIFFNESS (LB/SLIP/TIRE)	5000.00	5000.00	5000.00	5000.00
CAMBER STIFFNESS (LB/DEG/TIRE)	.00	.00	.00	.00
ALIGNING MOMENT (IN-LB/DEG/TIRE)	100.00	100.00	100.00	100.00
TIRE SPRING RATE (LB/IN/TIRE)	2000.00	2000.00	2000.00	2000.00
TIRE LOADED RADIUS (IN)	13.00	13.00	13.00	13.00
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)	15.00	15.00	15.00	15.00

Tractor / Mobile Home / 45K gross; 25 mph Crosswind; 45 mph Vehicle Speed.

		LEADING TANDEM AXLE		TRAILING TANDEM AXLE	
0	TRAILER NO. 1 REAR BRAKES	LEFT SIDE	RIGHT SIDE	LEFT SIDE	RIGHT SIDE
0	TIME LAG (SEC)	.1750	.1750	.1750	.1750
	RISE TIME (SEC)	.2500	.2500	.2500	.2500
	BRAKE TORQUE (IN-LB/PSI/BRAKE)	.0000	.0000	.0000	.0000
0	ANTILOCK KEY: 1 INDICATES ANTILOCK WILL BE USED			-1	

1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4. SUMMARY PAGE

Tractor / Mobile Home / 45K gross; 25 mph Crosswind; 45 mph Vehicle Speed.

0TRAILER NO. 1 PAYLOAD = .000 LBS.	EMPTY	LOADED
DISTANCE FROM TRAILER SPRUNG MASS CENTER TO REAR SUSPENSION (IN)	163.008	163.008
DISTANCE FROM TRAILER SPRUNG MASS CENTER TO GROUND (IN)	54.000	54.000
ROLL MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)	310000.000	310000.000
PITCH MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)	5560000.000	5560000.000
YAW MOMENT OF INERTIA OF TRAILER SPRUNG MASS (IN-LB-SEC**2)	5560000.000	5560000.000

0 TRACTOR PAYLOAD = .000 LBS	EMPTY	LOADED
DISTANCE FROM TRACTOR SPRUNG MASS CENTER TO REAR SUSPENSION (IN)	76.615	76.615
DISTANCE FROM TRACTOR SPRUNG MASS CENTER TO GROUND (IN)	44.000	44.000
ROLL MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)	15000.000	15000.000
PITCH MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)	75000.000	75000.000
YAW MOMENT OF INERTIA OF TRACTOR SPRUNG MASS (IN-LB-SEC**2)	75000.000	75000.000

0THE STATIC LOADS ON THE AXLES ARE:

AXLE NUMBER	LOAD
NS(1,1,1)	7131.200
NS(1,2,1)	16136.800
NS(2,2,1)	11116.000
NS(2,2,2)	11116.000
TOTAL	45500.000

0THE TRACTOR TOTAL MASS CENTER IS 50.909 INCHES BEHIND THE FRONT AXLE
THE TOTAL YAW MOMENT OF INERTIA IS 121584.500 IN-LB-SEC**2

0THE FIRST TRAILER TOTAL MASS CENTER IS 520.689 INCHES BEHIND THE KINGPIN
THE TOTAL YAW MOMENT OF INERTIA IS 5617262.400 IN-LB-SEC**2

```
1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.
                         Tractor / Mobile Home / 45K gross; 25 mph Crosswind; 45 mph Vehicle Speed.

0        SPRING TABLES
         -------------
             NO. OF LINES                 FORCE (LB)          DEFLECTION (IN)                 TABLE NO.
             ------------                 ----------          ---------------                 ---------

0                 4                                                                             -119.00
                                          -20000.00               -20.00
                                                .00                  .00
                                            9250.00                 7.20
                                           25000.00                 7.50
                                               (SPRING COMPRESSION ENVELOPE)
0
0

                                          -20000.00               -20.00
                                                .00                  .00
                                            8040.00                 7.20
                                           25000.00                 7.50
                                               (SPRING EXTENSION ENVELOPE)
0    SUSPENSION DEFLECTION CONSTANTS =    .08000 INCHES COMPRESSION,        .08000 INCHES EXTENSION.
0SPRING STATIC EQUILIBRIUM CONDITION:   2965.60 LB,       2.47 INCHES.         UNIT 1  SUSP 1  AXLE 1
0                 9                                                                             -131.00
                                          -26600.00               -11.00
                                                .00                -1.00
                                                .00                  .00
                                            5300.00                 1.00
                                            8650.00                 1.50
                                           12650.00                 2.00
                                           17300.00                 2.50
                                           22600.00                 3.00
                                           66000.00                 4.00
                                               (SPRING COMPRESSION ENVELOPE)
0
0

                                          -33000.00               -11.00
                                                .00                 -.80
                                                .00                  .20
                                            4000.00                 1.00
                                            6650.00                 1.50
                                           10650.00                 2.00
                                           15300.00                 2.50
                                           20600.00                 3.00
                                           53000.00                 4.00
                                               (SPRING EXTENSION ENVELOPE)
0    SUSPENSION DEFLECTION CONSTANTS =    .02000 INCHES COMPRESSION,        .02000 INCHES EXTENSION.
0SPRING STATIC EQUILIBRIUM CONDITION:   6918.40 LB,       1.38 INCHES.         UNIT 1  SUSP 2  AXLE 1
0                 4                                                                             -121.00
                                           -6000.00                -3.00
                                                .00                  .00
                                            8000.00                 2.00
                                           20000.00                 3.00
                                               (SPRING COMPRESSION ENVELOPE)
0
0

                                           -6000.00                -3.00
                                                .00                  .00
                                            7500.00                 2.00
                                           19000.00                 3.00
                                               (SPRING EXTENSION ENVELOPE)
0    SUSPENSION DEFLECTION CONSTANTS =    .05000 INCHES COMPRESSION,        .05000 INCHES EXTENSION.
0SPRING STATIC EQUILIBRIUM CONDITION:   5358.00 LB,       1.38 INCHES.         UNIT 2  SUSP 2  AXLE 1
0SPRING STATIC EQUILIBRIUM CONDITION:   5358.00 LB,       1.38 INCHES.         UNIT 2  SUSP 2  AXLE 2
```

Tractor / Mobile Home / 45K gross; 25 mph Crosswind; 45 mph Vehicle Speed.

0 MU-Y VS ALPHA TABLES

NO. OF LOADS	NO. OF VELOCITIES	TABLE NO.
3	1	-1

VELOCITY = 66.00 FT/SEC LOAD = 3000.00 LB

ALPHA (DEG)	MU - Y
.00	.00
1.00	.18
2.00	.33
4.00	.57
6.00	.71
12.00	.83

VELOCITY = 66.00 FT/SEC LOAD = 6000.00 LB

ALPHA (DEG)	MU - Y
.00	.00
1.00	.14
2.00	.25
4.00	.46
6.00	.58
12.00	.69

VELOCITY = 66.00 FT/SEC LOAD = 9000.00 LB

ALPHA (DEG)	MU - Y
.00	.00
1.00	.11
2.00	.19
4.00	.38
6.00	.52
12.00	.69

0 ROLL-OFF TABLE

0 SLIP

	ALPHA	.00	.04	.10	.50	1.00
0	.00	1.00	1.00	.90	.30	.10
0	4.00	1.00	1.00	.90	.30	.10
0	8.00	1.00	1.00	.90	.35	.13
0	12.00	1.00	1.00	.90	.42	.17
0	16.00	1.00	1.00	.90	.48	.22

0 MU-X VS. SLIP TABLES

NO. OF LOADS	NO. OF VELOCITIES	TABLE NO.
3	1	-2

VELOCITY = 66.00 FT/SEC LOAD = 3000.00 LB

SLIP	MU - X
.00	.00
.10	.68
.20	.80
.30	.77
1.00	.55

VELOCITY = 66.00 FT/SEC LOAD = 6000.00 LB

SLIP	MU - X
.00	.00
.10	.59
.20	.75
.30	.73
1.00	.50

VELOCITY = 66.00 FT/SEC LOAD = 9000.00 LB

SLIP	MU - X
.00	.00
.10	.44
.20	.70
.30	.69
1.00	.45

0 ROLL-OFF TABLE

0 SLIP

	ALPHA	.00	.04	.10	.50	1.00
0	.00	1.00	1.00	1.00	1.00	1.00
0	4.00	1.00	1.00	1.00	1.00	1.00
0	8.00	.75	.75	.75	.95	1.00
0	12.00	.50	.50	.60	.90	.95
0	16.00	.40	.40	.45	.85	.95

1HSRI/MVMA BRAKING AND HANDLING SIMULATION OF TRUCKS, TRACTOR-SEMITRAILERS, DOUBLES, AND TRIPLES - PHASE 4.

Tractor / Mobile Home / 45K gross; 25 mph Crosswind; 45 mph Vehicle Speed.

0 SEMI-EMPERICAL TIRE MODEL PARAMETERS

TIRE MODEL NO. -201.00

VARIABLE DESCRIPTION	INITIAL VALUE	D(VAR)/DLOAD	D(VAR)/DVELOCITY
0 NOMINAL CORNERING STIFFNESS (LB/DEG/TIRE	625.00	.10	.00
PEAK FRICTION VALUE (PER TIRE)	.90	.00	.00
LOCKED WHEEL FRICTION VALUE (PER TIRE)	.80	.00	.00
SLIP VALUE AT PEAK FRICTION (PER TIRE)	.20	.00	.00
NOMINAL PNEUMATIC TRAIL (IN/TIRE)	1.20	.00	.00
LATERAL STIFFNESS (LB/IN/TIRE)	10000.00	.00	.00
NOMINAL VERTICAL LOAD (LB/TIRE)	5000.00	N/A	N/A
NOMINAL VELOCITY (FT/SEC/TIRE)	88.00	N/A	N/A

Appendix C

A copy of the "Route Log Sheet" used by the observation teams is attached in this appendix.

16'-Wide Observation -- Route Log Sheet

Date________________ Time start__________________ Time end____________

Driver__________________________ Observer_______________________

Manufactured
Home Size: Width________________

Approx.
Length_______________

Tractor License #________________

Tractor # Axles_____________

Trailer # Axels_____________

Road Segment 1:_____________________ Monitor Start Time_____________________

Road Segment 2:_____________________ Monitor Start Time_____________________

Road Segment 3:_____________________ Monitor Start Time_____________________

Road Segment 4:_____________________ Monitor Start Time_____________________

Road Segment 5:_____________________ Monitor Start Time_____________________

Road Segment 6:_____________________ Monitor Start Time_____________________

Videotape Data Code______________________

Tape Coding Scheme:	16 or 14 Home Size	XX/XX Date of observ.	$$ Observer Initials	N Sequence Number of tape

Example: Carl Christoff observing 16' home on October 14, second tape of 3 -- videocassette should be coded: 1610/14CC2

Complete Videotape Data Code for Log Sheet would be:
1610/14CC1 - 1610/14CC2 - 1610/14CC3

Appendix D

A copy of the "Log Sheet for Vehicle Passing" used by the observation teams is attached in this appendix.

Log Sheet for Vehicle Passing

Date_______________________ Observer_______________________

Monitor Clock Time_______________________

Vehicle Over Left Edgemarker | **Vehicle NOT Over Left Edgemarker**

Total Stopwatch Time____________ | **Time out of lane**____________

Monitor Clock Time_______________________

Vehicle Over Left Edgemarker | **Vehicle NOT Over Left Edgemarker**

Total Stopwatch Time____________ | **Time out of lane**____________

Monitor Clock Time_______________________

Vehicle Over Left Edgemarker | **Vehicle NOT Over Left Edgemarker**

Total Stopwatch Time____________ | **Time out of lane**____________

Monitor Clock Time_______________________

Vehicle Over Left Edgemarker | **Vehicle NOT Over Left Edgemarker**

Total Stopwatch Time____________ | **Time out of lane**____________

Monitor Clock Time_______________________

Vehicle Over Left Edgemarker | **Vehicle NOT Over Left Edgemarker**

Total Stopwatch Time____________ | **Time out of lane**____________