TESTING THE POSITIONAL STABILITY OF MOTORCYCLE HELMETS

Hugh H. Hurt, Jr.
David R. Thom
James V. Ouellet
Head Protection Research Laboratory
United States
Paper No. 98-S10-P-30

ABSTRACT

Traditional motorcycle helmet performance standards provide a test for the strength and stiffness of the retention system. While such tests assure adequate strength, they do not assure that the helmet will be retained in place on the motorcyclist's head, even when securely fastened. The reason is that the geometry of the retention system can allow the helmet to roll off when contact or inertial forces are generated in a collision. Different types and styles of motorcycle helmets were tested to determine the susceptibility to roll off, i.e. "positional stability" (Thom et. al., 1997).

Tests were performed using two commonly used, adult sizes of headforms corresponding to standards of the U.S. Department of Transportation (DOT) and the International Standards Organization (ISO). The test results were validated by comparison with essentially identical tests on a large number of human subjects. The results of the human subject tests show a meaningful relationship to the laboratory test which employs a 10kg mass dropped 60cm to jerk the helmet forward to roll off.

The geometry of the retention system has a powerful effect on the ability of the helmet to resist forward roll off, in both laboratory and human subject tests. Also, there is considerable difference in the retention characteristics between DOT and ISO headforms, with the DOT headform more closely correlating with human subject data.

INTRODUCTION

The retention of the motorcycle helmet in place on the head of the motorcyclist is absolutely necessary to provide the full capability for impact attenuation and injury prevention. When contemporary helmet standards develop high levels of impact energy absorption in the structure of the helmet shell and liner, all protection can be lost if the helmet is ejected, or significantly displaced during accident events. Accident research has shown that there is significant benefit of motorcycle helmets in reducing the frequency and severity of head injury. Accident research also has shown that the ejection of the helmet during accident events occurs frequently, and many causes have been investigated (Gilchrist & Mills, 1992, Hurt, et. al., 1981, 1993, 1996, 1997, Mills & Ward, 1985, Newman, 1979, Otte, 1986, 1991, Snively, 1978).

As a part of research to update the FMVSS No. 218 (Thom et. al., 1997, Hurt et. al., 1996) the various helmet standards were collected and reviewed. A summary of the various retention system tests is presented in Table 1, including the static and dynamic tests which are supposed to provide for retention of the helmet during accident events. Actual mechanical failures of retention components during accidents are extremely rare, and most helmet ejections occur without significant damage to the components of chin strap webbing, hangers, rivets, and buckles, or equivalent fastening devices (Hurt et al,1981, Otte and Felten, 1985). For this reason, the test for positional stability of any motorcycle helmet is a critical requirement for successful protection.

In general, the ejection or displacement of the helmet during motorcycle accident events is accountable by loose fastening of the chin strap and loose fitting of the helmet. This lack of secure fit and fastening or failure to fasten the system at all accounts for most of the ejections of helmets in accidents. However, there are cases where the helmet is properly fitted and the retention system has been securely fastened, but the helmet is ejected. Of course, some of such cases occur when severe facial impact causes fractures of the mandible then support for the chin strap is destroyed and any helmet can be ejected. In many other cases, the design of the retention system does not have correct geometry, then contact and inertial forces acting on the helmet cause the helmet to respond by rotation upon the head and then be ejected or significantly displaced.

Table 1.
Retention System Test Methods and Failure Criteria

Standard	Year	Helmet Mounting	Static		Dynamic				Failure Criteria			Positional Stability		
			Preload	Test Load	Preload	Test Mass	Drop Height	Number of Tests	Dynamic Extension	Residual Extension	Buckle Slip	Test Type	Test Mass & Drop	Limit
FMVSS No. 218	1988	Headform	223 N, 30 sec.	1335 N, 120 sec.				One		≤ 25mm		None		
ANSI Z90.1	1992	Headform or Base			23 kg	38 kg*	120 mm	One	< 30mm			None		
AS 1698	1988	Headform	225 N, 30 sec.	1110 N, 120 sec.				One		< 25mm		None		
BS 6658	1985	Headform & Helmet Base			7 kg (support assembly)	10 kg	750 mm	Two (Strap not tightened)	1st 32mm 2nd 25mm	16mm 8mm		Forward Roll-Off	10 kg - 0.75 m	Stay on Head-form
CAN3-D230	1985	Helmet Base			7 kg	10 kg	750 mm	Two (Strap not tightened)	1st 32mm 2nd 25mm		8 mm Total	None		
Snell M-95	1995	Headform			23 kg	38 kg*	120 mm	One	≤ 30mm			Forward & Rearward Roll-Off	4.0 kg - 0.6 m	Stay on Head-form
ASTM F1446 (draft)	1997											Forward & Rearward Roll-Off	4 kg-0.6 m or** 10 kg-0.6 m	Stay on Head-form
ECE 22.4	1995				15 kg	10 kg	750 mm		< 35mm	< 25mm ***		Forward Roll-Off	10 kg- 0.5 m	< 30 degree angle change

* Preload removed "immediately prior" to test load.
** Drop mass and height to be specified by individual performance standards.
*** Measured 2 minutes after testing.

The most critical mobility of any helmet is rotation forward as if rolling off the head; backward rotation can happen but does not result in complete ejection or significant exposure of the head. When there is forward rotation of the helmet on the head, correct geometry of the helmet interior and retention system should cause tightening of the chin strap, thus resisting further displacement. If the chin strap anchor points are located far ahead of the center of helmet rotation, there is a tendency of the chin strap to loosen and rotation is not resisted, and the helmet may be ejected. Helmets with adverse design features, such as unfavorable locations for the chin strap anchor points, are known to have special vulnerability for ejection (Hurt, 1997, Mills & Ward, 1985, Otte & Felten, 1991)

The variations in helmet configurations affect the mobility of the helmet, with the partial coverage helmet being the most mobile and the full facial coverage helmet being the least mobile. As the helmet rotates forward on the head, the extent of coverage affects the resistance to that motion, with the obvious potential contact of the brow edge of the helmet with the nose and eyeglass frames (if worn). Denting of the EPS liner at the brow edge from contact with the nose and glass frame is typical evidence of the roll off motion. With the presence of the chin bar of the full facial coverage helmet, it is typical that contact of the chin bar with the motorcyclist's chin and sternum would limit the roll off motion. In this way, the full facial coverage helmet has an obstacle to the completion of roll off ejection. But the extra mobility of the partial coverage helmet may require special design considerations to resist roll off, e.g., a nape strap or Y-type chin strap harness. In these tests with human subjects, ejection rates for the partial coverage helmets ranged from 50 to 89% compared to 1 or 2% for full facial coverage helmets.

Fortunately, there is a tried and true method of preventing such roll off ejection by careful selection of the helmet, i.e., an "acceptance" test. It is recommended that when purchasing a helmet, the motorcyclist should try on the helmet, fasten the chin strap securely, then pull up on the posterior rim of the helmet. If the helmet displaces significantly or comes off, that helmet should be rejected and a different model, some other size, or a different manufacturer should be tried until such dangerous mobility does not occur. Of course, when the motorcyclist does not have the opportunity to make such a critical test, as for an occasional passenger, or a helmet already purchased without such test, roll off ejection in an accident is possible. Such a dangerous consequence clearly justifies a rigorous standard test of helmets to prevent such defective helmet designs from being offered to the unwary motorcyclist.

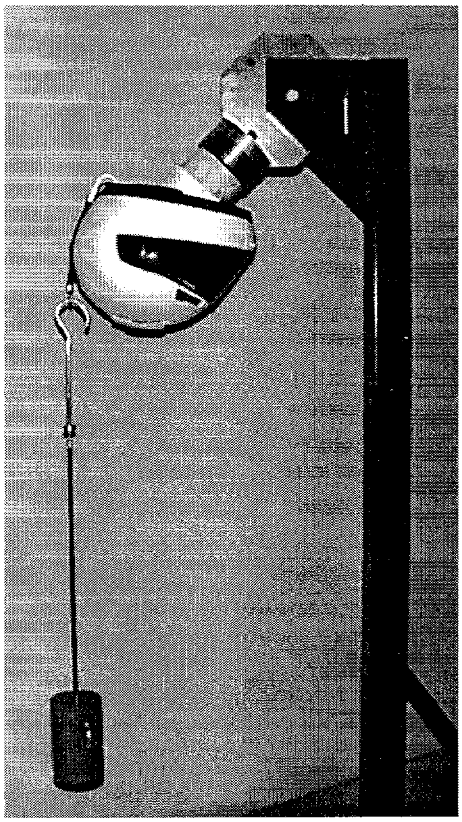
METHODOLOGY

During the study of updating the present FMVSS No. 218 (Hurt et. al., 1996), several methods of retention system testing were investigated (Thom et. al., 1997). In addition to the evaluation of testing for strength and stiffness, current methodology of testing for positional stability was investigated for possible incorporation into FMVSS No. 218. The specific elements to be included in the study were the most current roll off test methodologies, the effect of headform type, and correlation with human subjects.

The objective of the present research was to determine a minimum performance test of positional stability which could be adopted as a part of updating FMVSS No. 218. The suitable test procedure should provide reasonable simplicity and repeatability, and would correlate well with real world performance of helmets. It was decided to use the most current procedures developed by ASTM F08.53 committee (ASTM, 1995) to determine the positional stability of protective headgear. This method of testing was adopted by the Snell Memorial Foundation for the M95 motorcycle helmet standard. The test procedure involves placing the helmet on the test headform, which is supported at 45 degrees inclination from the vertical. A hook and strap are attached to the posterior rim of the helmet so that a forward roll off force can be applied there. A guide rod is attached to the strap and a sliding mass is allowed to drop along the guide rod, abruptly loading the helmet when the mass is arrested at the end of the guide rod. Figure 1 shows this apparatus with a test helmet in place. The current Snell test employs a 4kg mass dropped 60cm but the original ASTM draft standard employed a 10kg mass dropped 60cm for all motor sports helmets. This present investigation conducted tests with both 4kg and 10kg masses to determine the effect on various helmets.

An important reference standard for positional stability is the British Standards Institution standard BS 6658 (BSI, 1985), which uses a 10kg mass dropped 75cm. The BS 6658 utilizes a complex system of compliant surfaces on the headform, which is a complication thought to reduce repeatability of testing. The BS 6658 standard was not used in this study in favor of the less complicated ASTM F1446 draft.

Figure 1.
Roll-Off Test Apparatus



Using the ASTM F1446 draft procedure, six models of helmets were tested for positional stability. For each model set, all available sizes were obtained for testing, and since some models have more available sizes, the number of tests per set varies. Several helmets were tested on each size of headform, e.g., sizes XXS, XS and S typically would fit the DOT Small and ISO E size headforms, but would be too small for testing on the larger headforms. Of course, larger helmets were not tested on headforms that were clearly too small and inappropriate. For this laboratory testing, the roll off test results were collected according the following codes:

1. No movement
2. Some movement, definitely retained
3. Retention marginal, possibly ejected with greater force
4. Ejected with resistance
5. Ejected easily, minimal resistance
6. Retained on the 4kg mass test; ejected on the 10kg mass test

The results of the laboratory tests with DOT and ISO headforms are shown in Table 2.

In order to validate the findings of the laboratory roll off test, further tests were conducted with volunteer human subjects, and the results are shown in Table 3. Test procedures were carefully explained to each subject, and measurements were made of the head circumference in the horizontal plane (headband) and coronal plane (underneath the chin). Subjects were instructed to put on the helmet and fasten the chin strap so that it was in contact with the skin underneath the chin, but loose enough to slide one finger comfortably between the chin strap and the chin. Subjects were instructed to rotate the helmet rearward (to check for rearward stability) and then forward. Subjects were instructed to pull forward vigorously on the helmet, enough to cause discomfort but not to the point of causing pain. Some helmets would come off quite easily, others would come off only with discomfort. Since this test was controlled completely by the subject, each subject could monitor helmet movement, personal discomfort and sense how likely the helmet was to come of with additional force.

The helmets tested by the human subjects included two full facial coverage models, one full coverage model and three partial coverage models. Four to six sizes were available in each model. Subjects tried on two sizes of each model and were asked to determine the size which provided the "best fit" in each model when multiple sizes were tried. The test methodology required the first trial of the subject to use the helmet size most likely to be their "best fit", as correlated with the headband measurement. If the subject was unable to pull off that size helmet, the next larger size was tried because motorcyclists often use a helmet that is too large. Conversely, if the rider was able to pull off the "best fit" in a particular model, the next smaller size was tried to see if that could be pulled off as well. For this human subject testing, the roll off test results were collected according the following codes:

1. No movement
2. Some movement, definitely retained
3. Retention marginal, possibly ejected with greater force
4. Ejected with resistance
5. Ejected easily, minimal resistance

The results of the human subject tests are shown in Table 3. An important factor affecting the roll off resistance of a motorcycle helmet is the match between the exterior contour of the motorcyclist's head and the interior contour of the helmet. Ideally, every motorcyclist would be able to acquire a helmet that gives a comfortable and safe fit which limits the mobility on the head. However, the irregularities of shapes of the human head are numerous and a few motorcyclists will have difficulty in acquiring a helmet that has that "best fit" without some problems of contour match. The tendency is to accept a helmet that may be too large simply to avoid uncomfortable local contact areas, and this could affect retention performance. If the design of the helmet intentionally provides specific geometry to resist roll off, slight variations in helmet fit will not adversely affect the retention performance for those motorcyclists with heads that are difficult to fit. Finally, there will be a very few extreme head shapes which will defeat even the most careful designs, and that particular motorcyclist must use great caution in helmet selection, and should accept only a full facial coverage helmet which does well in the "acceptance" test.

DISCUSSION

The laboratory tests confirm the susceptibility to roll off ejection of the partial coverage helmet, in comparison with the full coverage and full facial coverage helmets. It is important to note that the six helmet models selected for these tests were not selected randomly from the total helmet population. Some helmet models were selected because of known performance from previous laboratory testing and accident research, in order to ensure a wide range of helmet responses in the proposed tests.

As expected, the full facial coverage helmets provide the most satisfactory performance for both laboratory and human subject testing, with ejection occurring in one or two percent of the tests. While the full facial models used in these tests are not a complete representation of all full facial helmets available, the results are indicative of significant resistance to roll off ejection simply by the greater coverage and presence of the chin bar. Because of such a physical obstacle to the roll off displacement, any securely fastened full facial coverage helmet which suffers roll off must have the retention system anchor points misplaced in obviously defective locations (Hurt, 1997, Mills & Ward, 1985, Otte & Felten, 1991).

Also as expected, the partial coverage helmets selected for these tests showed a high frequency of ejection for both laboratory and human subject tests, with some models failing almost all tests. The design of the retention system for these partial coverage helmets must incorporate special provisions to prevent such gross susceptibility, otherwise the motorcyclists using these helmets are at peril. The high ejection rates completely verify the need for a minimum performance roll off test for these helmets which are otherwise qualified to static and dynamic strength tests.

The laboratory tests show that the DOT headforms retain both full coverage and full facial coverage helmets better than the ISO headforms, but the ISO headforms retain the partial coverage helmets better than the DOT headforms. The small number of laboratory tests limits the significance of the headform effects, and there are inconsistencies in the results for DOT and ISO headforms. Resolution of these problems could be satisfied only with a larger number of laboratory tests, or simply the headform requirements of other areas of helmet testing. Significant differences are not determined at this point in this research.

The ASTM draft standard (ASTM, 1995) employs the ISO headforms but could be modified simply to specify the current DOT headforms. Either the DOT or ISO headforms could be specified for use since most manufacturers and test laboratories usually have both sets of headforms. The use of the DOT headforms would require further tests and validations since no such testing was done during the ASTM F08.53 Committee preparation of the draft procedure.

Table 2.
DOT and ISO Test Headform Forward Roll-Off Result Summary
(Human subject data included for comparison)

Headforms (All sizes combined)	Helmet (Count in category)	Retained, minimal movement	Retained, some movement	Retained, possibly ejected with greater force	Ejected with resistance	Ejected with minimal resistance	Retained in 4kg test, ejected on 10 kg test	No. Tests	Percent Ejected
DOT	Partial 1	0	1	0	2	1	3	7	86
ISO	Partial 1	1	1	0	0	0	7	9	78
Human	Partial 1	0	6	12	70	76	N/A	164	89
DOT	Partial 2	2	2	0	0	0	2	6	33
ISO	Partial 2	2	4	0	0	0	0	6	0
Human	Partial 2	8	55	22	27	15	N/A	127	33
DOT	Partial 3	1	1	0	0	1	1	4	50
ISO	Partial 3	1	1	0	0	1	1	4	50
Human	Partial 3	5	36	3	11	29	N/A	84	48
DOT	Full Coverage	0	4	0	1	0	4	9	56
ISO	Full Coverage	0	0	0	0	4	5	9	100
Human	Full Coverage	2	29	26	66	46	N/A	169	66
DOT	Full-Facial 1	2	5	0	0	0	0	7	0
ISO	Full-Facial 1	0	4	1	0	1	1	7	29
Human	Full-Facial 1	58	68	2	1	0	N/A	129	0.8
DOT	Full-Facial 2	0	6	2	0	0	0	8	0
ISO	Full-Facial 2	0	8	0	1	0	0	9	11
Human	Full-Facial 2	29	76	7	1	0	N/A	140	0.7

Table 3.
Comparison of Human Subject and Test Headform Ejection Data

Count (%)	Retained, minimal movement	Retained, some movement	Retained, possibly ejected with greater force	Ejected with resistance	Ejected with minimal resistance		Total Ejected Count, (%)
Helmet			*Human Subjects*				
Partial 1	0	6 (5.7)	12 (7.3)	70 (42.6)	76 (46.3)		146 (89.0)
Partial 2	8 (4.8)	55 (33.5)	22 (13.4)	27 (16.5)	15 (9.1)		42 (33.0)
Partial 3	5 (6.0)	36 (42.9)	3 (3.6)	11 (13.1)	29 (34.5)		40 (47.6)
Full Coverage	2 (1.2)	29 (17.2)	26 (15.4)	66 (39.1)	46 (27.2)		112 (66.3)
Full Facial 1	58 (45.0)	68 (52.7)	2 (1.6)	1 (1.2)	0		1 (0.8)
Full Facial 2	56 (40.0)	76 (54.3)	7 (8.0)	1 (1.1)	0		1 (0.8)
Test Headforms (DOT and ISO Combined)			* Failed retest with 10 kg weight. ** Passed retest with 10 kg weight			Retained on 4 kg test, ejected on 10 kg test	
Partial 1	1 (6.3)	2 (12.5)	*	2 (12.5)	1 (6.3)	10 (62.5)	13 (81.3)
Partial 2	4 (33.3)	6 (50.0)	2 (16.7)*	0	0	2 (16.7)	2 (16.7)
Partial 3	2 (25.0)	2 (25.0)	2 (25.0)*	0	2 (25.0)	2 (25.0)	4 (50.0)
Full Coverage	0	4 (22.2)	9 (50.0)*	1 (5.6)	4 (22.0)	9 (50.0)	14 (77.6)
Full Facial 1	2 (14.3)	9 (64.3)	1 (7.1)**	1 (7.1)	0	1 (7.1)	2 (14.2)
Full Facial 2	0	14 (82.4)	2 (11.8)**	1 (5.9)	0	0	1 (5.9)

Table 4.
Summary of 10 kg Laboratory Tests and Human Subject Test Results

	Human Subject Ejection %	DOT Headform 10kg Ejection %
Partial 1	89	86
Partial 2	33	33
Partial 3	48	50
Full Coverage	66	56
Full Facial 1	0.8	0
Full Facial 2	0.7	0

Comparison of the data for human subjects and test headforms shows that the 4kg-60cm test is not a rigorous test of positional stability for motorcycle helmets. It shows that helmets which passed that roll off test on headforms were easily ejected by the human subjects. Note in that for helmet "Partial 1" the ejection rate was 89% for human subjects, 86% for the 10kg-60cm tests, but only 19% for the 4kg-60cm test. Any acceptable laboratory test procedure for helmet retention should produce results which are approximately the same as for human subjects, thus providing real world protection for the motorcyclist. The 4kg-60cm test as promulgated by ASTM and used in the Snell M95 standard will not assure retention and the 10kg-60cm test appears to be required for rigorous testing. Table 4 shows the human subject and laboratory test data for the 10kg-60cm roll off test.

CONCLUSIONS

The application of the ASTM draft standard (ASTM, 1995) with DOT headforms can provide a suitable minimum performance requirement for positional stability of motorcycle helmets. This type of test is necessary to eliminate unsafe helmets from the current market offerings. This test is clearly justified by the high level of correlation with human subject test results.

The 4kg-60cm test as promulgated by ASTM and in use by Snell Memorial Foundation is not sufficiently rigorous to fail helmets that are susceptible to roll off ejection, and the 10kg-60cm test is the minimum necessary energy.

ACKNOWLEDGEMENT

This research was conducted for the U.S. Department of Transportation, National Highway Traffic Safety Administration under Contract DTNH22-97-P-02001. The authors gratefully acknowledge the cooperation and assistance of William J. J. Liu, Ph.D., the NHTSA Contract Manager, and Christopher Lash of NHTSA Safety Assurance.

REFERENCES

American National Standards Institute, "American National Standard for Protective Headgear for Motor Vehicle Users". ANSI Z-90.1, ANSI, 1992.

American Society for Testing and Materials, "Standard Test Methods for Equipment and Procedures Used in Evaluating the Performance Characteristics of Protective Headgear". ASTM F 1446-95a, 1995.

American Society for Testing and Materials, "DRAFT-Standard Specification for Helmet Stability and Roll-Off Testing". ASTM, 1995.

British Standards Institution, "British Standard Specification for Protective Helmets for Vehicle Users". BS 6658, 1985.

Canadian Standards Association, "Standard for Protective Headgear in Motor Vehicle Applications". CSA CAN3-D230, 1985.

Federal Motor Vehicle Safety Standard No. 218, CFR 571.218, U.S. Department of Transportation, National Highway Traffic Safety Administration, 1988.

Gilchrist, A. & Mills, NJ, "Critical Assessment of Helmet Retention Test Methods, IRCOBI 1992.

Gilchrist, A, Mills, NJ, & Khan, T, "Survey of Head, Helmet and Headform Sizes Related to Motorcycle Helmet Design". Ergonomics 31, No. 10, 1988, pp. 1395-1412.

Hurt, HH. "Logic Analysis of Helmet Ejection". USC-HPRL Report, 1997

Hurt, HH. "Logic Analysis of Helmet Ejection". USC-HPRL Report, 1997

Hurt, HH, Ouellet, JV & Thom, DR, "Motorcycle Accident Cause Factors and Identification of Countermeasures"; Vol. I Technical Report, Vol. II Appendices and Supplemental Data, NTIS PB-206 443, PB-206 450, 1981.

Hurt, HH & Thom, DR, "Accident Performance of Motorcycle and Bicycle Helmets". ASTM STP 1229-Head and Neck Injuries in Sports, ASTM 1993.

Hurt, HH, Thom, DR & Smith, TA, "Updating the Twenty Year Old DOT Helmet Standard (FMVSS No. 218)". 40th Proceedings of the Association for the Advancement of Automotive Medicine, 1996.

Mills, NJ & Ward, RF, "The Biomechanics of Motorcycle Helmet Retention". IRCOBI, 1985.

Newman, JA, "The Dynamic Retention Characteristics of Motorcycle Helmets". Biokinetics/Ministry of Supply and Services, Ontario, Canada, September, 1979.

Otte, D, "Technical Demands of Safety in the Design of Crash Helmets for Biomechanical Analysis of Real Accident Situations". SAE 912911, 1991.

Otte, D & Felten, G, "Requirements on Chin Protection in Full-Face Helmets for Motorcyclist Impact and Injury Situations". Proceedings 1991 International Motorcycle Conference, Institut fur Zweiradsicherheit, 1991.

Otte, D, Appel, H & Suren, EG, "Recommendations for Improvement of the Injury Situation for the Users of Two-Wheel Vehicles". IRCOBI September 1986.

Snell Memorial Foundation, "1995 Standard for Protective Headgear for Use with Motorcycles and Other Automotive Vehicles". Snell Memorial Foundation, 1995.

Snively, GS, "Head Protection: Preventive Medicine in Traffic Safety, Proceedings AAAM pp. 69-80, 1978

Standards Association of Australia, "Methods of testing Protective Helmets". AS 2512.1-1984, AS 2512.2-1983, AS 2512.3-1981, AS 2512.5-1986

Thom, DR. Hurt, HH, Smith, TA & Ouellet, JV, "Feasibility Study of Upgrading FMVSS No. 218, Motorcycle Helmets". Final Report, US Department of Transportation, National Highway Traffic Safety Administration, DTNH22-97-P-02001, 1997.

United Nations, Uniform Provisions Concerning the Approval of Protective Helmets and of Their Visors for Drivers and Passengers of Motor Cycles and Mopeds, United Nations E/ECE/22.4, May, 1995.