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Beyond Crashworthiness A Critical Review of Structural Demand Damage Mechanisms and MASH Compliance in Permanent Concrete Median Barriers

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Abstract

Permanent concrete median barriers are generally considered rigid roadside safety systems; however, their behavior depends on the interplay between barrier geometry, barrier height, reinforcing, anchorage systems, supporting structure, vehicle attributes, and impact conditions. With the introduction of the MASH, the difficulty level of the single-unit-truck Test Level 4 impact increased, and shortcomings of using only historical crash test acceptance criteria became evident. This literature review focuses on permanent concrete barrier geometries, MASH evaluation criteria, observed displacements and damages, impact forces and structural demands, and full-scale crash tests versus finite element nonlinear analyses. Data from crash-test reports, experimental studies, and LS-DYNA analysis reveal that the containment and stability of vehicles cannot be determined solely based on the nominal strength of the barrier. While geometry and height influence vehicle climbing and rollover tendencies, reinforcing, deck/foundation continuity, and load transfer define cracking, punching shear, and plastic deformation. While full-scale testing provides a basis for safety evaluation, validated nonlinear simulations allow analyzing force history, failure modes, and variants that cannot be tested once. In view of the current literature, the approach to evaluating the behavior of permanent concrete median barriers should encompass a combined consideration of MASH crashworthiness criteria, structural capability, and validated simulations. The remaining challenges relate to the proper definition and reporting of barrier deformations and damages, more advanced dynamic force definitions, validation of concrete failure models, and performance-based criteria for extrapolation of test results to similar barriers.

Keywords: concrete median barrier; MASH; NCHRP Report 350; crash testing; LS-DYNA; impact force; structural demand; barrier damage

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1 INTRODUCTION

Permanent concrete median barriers are extensively utilized for separation of traffic lanes traveling in opposite directions and reduction of potentially lethal cross-median crashes. The main roles of such systems include containing an out-of-control vehicle, redirection of the latter without roll-over or penetration, and minimizing the risks to the driver and other road users. Despite the rigid barrier designation, local cracking, yield of reinforcement, displacement of connections, rotation of foundation, deck deflection, and attachment damage can all affect the interaction between the vehicle and the barrier and the final state of the latter [1-3]. In accordance with the same system-level idea, the performance of a glulam timber rubrail and noise wall assembly subjected to crash testing is defined by the integrated effect of rails, posts, connections, and wall arrangement [4].

The introduction of the Manual for Assessing Safety Hardware (MASH) has resulted in changes in the conditions of testing for longitudinal barriers [2-3]. MASH has succeeded the impact evaluation procedures specified in NCHRP Report 350 in 2009 and has been released as a revised second edition in 2016 [1-3]. The most essential change is related to

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the increase in the nominal characteristics of TL-4 vehicle. According to NCHRP Report 350, the mass of the single-unit truck used for TL-4 test was 8,000 kg and the impact speed was 80 km/h [1]. MASH has increased these figures to 10,000 kg and 90 km/h respectively while keeping the nominal impact angle constant and equal to 15 degrees [2-3]. This has increased the nominal TL-4 impact severity approximately by 56 percent [5]. As a result, satisfactory performance under NCHRP Report 350 does not automatically imply adequate containment and redirection of the heavier truck specified by MASH TL-4 test [5-7].

This issue becomes crucial for permanent concrete barriers because many in-service barriers have been designed, tested, or approved prior to MASH introduction. Such a barrier can provide necessary flexural strength while lacking some favorable attributes including insufficient height, aggressive lower slope, discontinuity, or attachment attached to its top surface. On the other hand, a barrier with visible damage might still be acceptable from the standpoint of crashworthiness if it can contain and redirect the impacting vehicle without causing any unacceptable occupant risk [6,8-11]. Therefore, structural capacity and crashworthiness are two related but different measures of performance. Crash testing of the flared buried-in-backslope guardrail end terminal shows that the combination of approach direction, embedment, and surrounding ground makes the system rather than a discrete element an appropriate object of evaluation [12].

The available literature includes full-scale test results, structural experiments, numerical modeling, design considerations, and impact evaluation documents. Individual publications focus on a particular result including vehicle behavior, barrier damage, lateral capacity, force history, or compliance with some particular test matrix. Any synthesis should incorporate the link between such results and differentiate the evidence obtained during physical crash testing from the one obtained through quasi-static analysis or numerical simulation [6-9]. For barriers supported by soil or embedded in the foundation, the interpretation of the structural demands is also based on the characterization and constitutive representation of the material. Full-scale triaxial tests have shown the stress- and confinement-dependent behavior of rockfill materials [13] while a review of dynamic soil-structure interaction models has revealed that constitutive model defines predicted stiffness, deformation, and loading [14]. SPH+FEM and EFG+FEM hybrid simulations have illustrated how large deformations and interface behavior can be captured when classical formulations fail [15].

This review is concentrated on permanent concrete median and related barrier systems evaluated through full-scale testing, lateral-load testing, and nonlinear dynamic analysis. The following three questions guide the discussion: (1) how the barrier profile and structural configuration affects displacement and damage; (2) how impact forces are measured, calculated, or estimated and transferred into structural demands; and (3) how the evidence provided by these sources either supports or refutes the compliance with MASH. Portable work-zone barriers are not included in the list of system classes considered, although some studies are used when clarifying modeling, validation, and load transfer issues.

2 Review Methodology

The review was structured around an evidence-based comparison rather than just a compendium of barrier tests. Sources were selected for their relevance to concrete barriers that are permanent, bridge rails, median barriers, MASH, NCHRP Report 350, structural resistance, full-scale crash testing or finite element analysis. Standards and synthesis documents were used to specify test criteria and evaluation procedures [1-3,7]. Research papers and peer-reviewed articles were then employed to extract evidence about geometry, material, reinforcement, test vehicle, impact conditions, measured/estimated force, barrier deflection, visible damage, vehicle behavior, and compliance.

The evidence was categorized in four groups. The first one contains primary standards and design specifications. The second group consists of crash-test reports based on full-scale crashes. These are the most powerful direct evidence of system-level crashworthiness. The third group includes

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laboratory experiments on lateral resistance, yield line, punching shear, and connections. Finally, the fourth group is made up of numerical studies. These are LS-DYNA analyses used to recover the force history, perform parameter sensitivity studies, or to compare different configurations [8-9,16-21].

Comparisons were performed only when the underlying measures were comparable. Peak contact force, filtered force, equivalent static design load, and barrier capacity were not regarded as identical quantities. Likewise, dynamic deflection, permanent set, local concrete damage, and structure deformation were recorded as different response measures. It is essential because two barriers can have identical peak contact force but different damage or identical visible damage but different vehicle trajectory [8-9,16].

MASH compliance is treated as a system-level conclusion about the system being tested under specified test matrix and criteria, not as a material property or direct implication of calculated capacity. A positive outcome of one test configuration was not applied to barriers with other height, slope, reinforcement, foundation, deck connection, flare or top-mounted hardware. When engineering equivalence was discussed in the literature, it was treated as supporting evidence [6-7].

3 Permanent Concrete Median Barrier Profiles

Profiles that control the location and orientation of wheel and body contacts influence the stability of vehicles climbing and rolling on a barrier as well as lateral loading transfer heights. Consequently, the selection of a profile cannot be decoupled from height of a barrier because the lower geometry of two barriers might lead to different stability results depending on the effective height of containment [5-6,22].

The New Jersey safety shape barrier includes a sloped lower face and a sloped upper face separated by a break point. The development of such a barrier has been focused on limiting wheel contacts while redirecting the passenger vehicle. The problem with this design is that under heavy impacts, wheel climb and passenger vehicle body contact with the upper slope may cause the roll. F-shape barriers include a modified geometry of the lower slope and break point aiming to reduce passenger vehicle lift during impacts. At the same time, the barrier still has a constructible slip-formed section. Both profiles have been historically tested and proven effective according to their development criteria. However, the past success of such designs does not solve the problem of the performance of the MASH TL-4 truck [1,5,22].

The single-slope barriers include a consistent traffic side slope which is approximately 9.1 degrees from vertical. The geometry is less sensitive to overlays since the rise of the surface of the road will not create the same effect as changing a slope break point. In full scale, free-standing and structurally supported single-slope barriers have shown the importance of the overall height, base restraint, and continuity in controlling roll and performance of the truck barrier [22-23]. As a result, this profile seems to be attractive for the permanent medians. However, different heights or base details of the single-slope barriers should not be considered equal without any proof.

The vertical-face barriers limit wheel climb resulting from a sloped face and provide good containment for heavy vehicles when there is enough height and structural capacity. However, this design may influence passenger-vehicle accelerations and local contact forces. Open and aesthetic concrete rail barriers include additional factors that influence performance because of open spaces, posts, and top rails which change the loading path and possible snagging or intrusion of the vehicle [17,24].

The attachments and geometrical transitions are equally significant to a basic profile. The glare screens, fences, signs, and other hardware mounted on the barrier will change the envelope of the vehicle, introduce snagging points, and add load to the barrier and its anchorage. In full scale, the tests of barriers with glare screens or top-mount fences prove that the combination of installations, and not only a concrete barrier, should be analyzed [11,25]. The flared barriers change the effective angle of the impact as well as the sequence of vehicle contacts. The tests of cast-in-place flared barriers have proved that the flare rate is one of the system variables relevant to MASH performance [10].

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In conclusion, the literature does not allow to rank profiles using a single universal criterion. The barrier that minimizes passenger-vehicle climb does not necessarily minimize the heavy-truck roll. And taller barrier sections which improve containment may increase the structural demands on the base of the barrier. The meaningful comparisons should include test level, impact condition, barrier height, support configuration, and vehicle type simultaneously [5-8].

4 MASH Requirements and Evaluation Procedures

MASH establishes criteria for crash test matrices, impact scenarios, evaluation criteria, and documentation needs for roadside safety devices [2-3]. Longitudinal barriers require tests based on the selected test level and various types of vehicle categories in order to test for containment, redirection, occupant protection, and stability. The small-car and pickup truck tests are sensitive to snagging, pocketing, occupant compartment deformation, and acceleration criteria, while higher test levels use heavier vehicles to test for containment, rollover and structural adequacy [2-3,6] (see Figure 1).

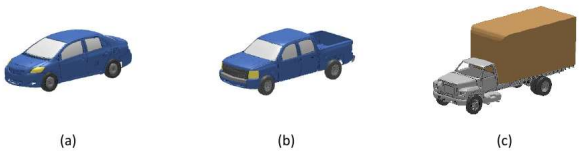

Figure 1. MASH test vehicle models: (a) 1100C, (b) 2270P, and (c) 10000S. Source: Figure 2.2 in Ref. [10].

The evaluation for a MASH compliant barrier is not simply about the ability of the barrier to keep the test vehicle in the road. The barrier must contain and redirect the test vehicle without penetration, override, or underride; the detached parts of the barrier shall not constitute an unacceptable risk; the occupant risk criteria and vehicle deformation shall be within acceptable limits; and the post-impact path shall not constitute an unacceptable hazard [2-3].

In the case of TL-4, the test consists of a 10,000 kg single-unit truck impact at 90 km/h and 15 degrees, which is an significant change compared to the NCHRP Report 350 test criteria [1-3,5]. The nominal kinetic energy of the vehicle does not itself represent the demand on the barrier since only some of the vehicle's momentum and energy are transferred laterally and its transfer is a function of rotation, tire interaction, crush, redirection, and time duration. However, it is clear from these changes that it provides a reason for reassessing old barriers, especially if their height or capacity was borderline in the previous criteria [5-7].

Barrier height is critical for stability of heavy vehicles. Analysis and testing have established that the minimum rail height and effective height of force application is important for control of roll and avoidance of passage of the body or cargo region over the barrier [5]. In evaluating barrier height, one should take into account the installed condition of the barrier taking into consideration pavement overlays, curbs, grade changes, and adjacent surfaces. The nominal drawing height might not be reflective of the actual effective height experienced by the vehicle.

The compliance with the MASH criteria is shown most straightforwardly in the appropriate full-scale test series. Engineering analysis, comparison with an existing tested system and validation of simulation can support decision-making in cases of minor modification. However, the comparisons shall include the features which are the key to the performance of the barrier. Hovde has proposed a methodology for evaluating permanent concrete barriers for which new physical testing is unfeasible, involving geometry, structural capacity, and similarity to successfully tested barriers [6]. In later synthesis, the necessity to compare bridge railing design requirements to crash performance observations and to acknowledge the uncertainties of simplified structural load models has been emphasized [7].

A properly defensible claim of compliance will then identify the test level, system configuration, tests used or prior evidence, and the range of extrapolation. Calling a barrier MASH compliant without these qualifications can hide significant differences in height, foundation, reinforcement or attached hardware.

5 Barrier Displacement Damage and Failure Modes

Continuous barriers usually demonstrate limited global displacement. However, this rigidity does not mean that there is no damage in the system. The

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damage mechanisms include flexural cracking, crushing/spalling, reinforcing bar yielding, punching shear, base rotation, joint opening, anchorage failure, deformation of the deck or slab [8-9,16,26], which must be clearly stated in relation to displacement: maximum transient displacement, residual displacement, local face displacement, displacement of the support structure.

In relation to flexural response, a yield-line analysis is traditionally applied. In the context of bridge railing design, the classical triangular mechanism is used to assess the resistance length and capacity of the barrier. Comparison of calculated results and experiments indicates that in some cases, the actual cracking is better represented by modified or trapezoidal mechanisms and classical approach is conservative [8]. In Loken et al.'s sample, on average, the capacity estimates were 47% larger if alternative assumptions were applied, although in one case, the governing damage mechanism was punching shear rather than flexural [8]. Thus, even a more accurate flexural estimate does not mean that local failure should not be assessed.

Local punching shear is significant if the impact load is concentrated over a relatively small area and barrier or deck is unable to redistribute the load properly. Local geometry, reinforcement pattern, concrete strength, load height, and connection continuity are the key parameters of this damage mechanism [8-9]. Static lateral load tests are useful to observe the cracking and estimate ultimate resistance, but due to difference in loading rate and load distribution, these tests are not sufficient to establish crashworthiness [9,16]. Changes in material properties may affect both damage initiation and nature of the damage. UHPC barriers and connections can provide increased strength and crack resistance with reduced section dimensions, while fiber reinforced or rubberized concrete may affect energy absorption, crack distribution and residual integrity [27-29]. These advantages should be analyzed along with connection response and vehicle response as material modification alone does not guarantee proper redirection.

Failure mechanisms of discontinuous systems are especially important as barrier ends, joints, transitions, discontinuities in the foundation and vicinity of attachments are able to disrupt longitudinal force redistribution. If a barrier behaves as a long member outside these regions, then in close vicinity of discontinuity it behaves as a member of a shorter effective length. Experiments and analytical models of restrained, unattached and foundation-supported barriers demonstrate the significance of base details and continuity [22-23,26].

Serviceability in post-impact state is not adequately represented by a pass/fail crash test result. It is possible that a barrier meets all containment criteria, but nevertheless needs to be repaired due to the presence of wide cracks, exposed rebars, permanent offset, damaged attachments, or decrease in the residual capacity. The literature would benefit from the reports about crack width, spall dimensions, residual displacement, reinforcement condition, and repair decision, especially for barriers that are expected to be operated after the impact.

6 Impact Forces and Structural Demand

The impact force represents one of the most challenging parameters to compare among concrete barrier studies. Indeed, the contact between the vehicle and barrier generates a highly dynamic and distributed force. Different values could refer to an instrumented contact force, a force estimated from the vehicle acceleration, the support reaction, an unfiltered numerical contact force, an equivalent static design force or other related forces. Such parameters differ from each other and cannot be mixed without specifying the processing procedure [7-9,18].

The demand on the barrier results from the vehicle mass and speed, impact angle, stiffness and geometry of the vehicle, tire interaction, geometry and height of the barrier, length of the contact, deformations of the vehicle and barrier. Simple calculation of the momentum can be used to estimate the nominal lateral component of the impact velocity, which cannot be used to calculate the peak structural force due to unknown duration and force distribution. Similarly, kinetic energy can be used to evaluate the nominal severity of the impact but not the barrier performance [5,7].

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In crash tests, full-scale or component-level, we have access to the information about the vehicle accelerations, fast video imaging and even some force-related data, but there is no way to directly measure the distributed contact force. However, numerical modeling allows us to retrieve the history of contact forces and forces in connections, but the high frequency response of the signal is very sensitive to contact model, discretization, vehicle and material models, and output filtering [18-21]. Thus, the peak reported is meaningful only if the signal definition and filter were mentioned.

Structural design procedures commonly consider the impact as an equivalent lateral load applied to the predefined length and height of the barrier. It is a convenient way of design, however, such an approximation does not reflect the actual contact process. The analysis comparing yield-line capacity, punching shear capacity, experimentally measured lateral resistance, and numerically simulated demand revealed that too conservative capacity models and improperly evaluated demand may result in conflicting findings [7-9]. Thus, our aim is not to make the single peak force comparable with the nominal static capacity, but to prove that our load and resistance models capture the actual failure mechanisms with adequate safety margin.

Material strength increase due to dynamics and effect of inertia increasing participation of the barrier in resistance can be opposed by local peak forces, which activate limited barrier resistance. The interaction of such phenomena explains why it is impossible to relate the static and dynamic force measures with a single coefficient. Experimental and numerical evidences show the need of configuration specific evaluation of load distribution, participating length, foundation restraint, and failure mode [8-9,16].

At least four outputs should be reported separately: peak and filtered vehicle-barrier contact force; base shear and overturning moment; local demands resulting in concrete and reinforcement damage; global displacement of the barrier or the supporting structure. The presentation of all these outputs will allow meaningful comparison of crash tests, component tests and numerical analyses.

7 Full Scale Crash Tests versus LS DYNA Predictions

Full-scale crash testing is the most straightforward technique for assessing the coupled response of the vehicle-barrier-support system under the given MASH test criteria. This includes tire and suspension behavior, vehicle deformation, occupant compartment response, barrier damage and post-impact trajectory. The limitations are cost, variability among tests, instrumentation issues, and the limited configurations that can be tested [2-3, 10-11, 23].

Non-linear finite element analysis, particularly with LS-DYNA, augments testing by allowing time histories and other internal responses to be obtained that are hard to measure directly. With a validated model, different barrier heights, profiles, reinforcements, foundations, impact points, vehicle orientations, and materials can be assessed. It can help in identifying which response is governed by vehicle instability, barrier deformation, punching action, connection failure or supporting structure response [18-21, 30].

Validation is the crucial requirement. Matching in vehicle trajectories alone is inadequate when barrier deformation, acceleration history, contact history, and damage pattern are poorly simulated. On the other hand, matching just a peak force can be deceptive as such peaks are highly sensitive to noise and filtering. An adequate validation requires comparison of multiple independent responses involving vehicle speed and orientation, wheel and body contact, barrier displacement, damage pattern, acceleration measurements and timing and duration of key contacts [18-21].

Marzougui et al. compared a Chevrolet Silverado impact with a New Jersey barrier and showed the benefit of comprehensive crash test versus simulation comparisons for assessment of vehicle and barrier responses [18]. Atahan showed how a finite element model of a portable concrete barrier was capable of simulating system dynamics and vehicle interaction, illustrating modeling considerations that apply even to permanent barriers although the boundary conditions are different [19]. Consolazio et al. illustrated the efficiency of combination of simulation with full

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scale testing in the development of a low profile concrete work zone barrier [20] (see Figure 2).

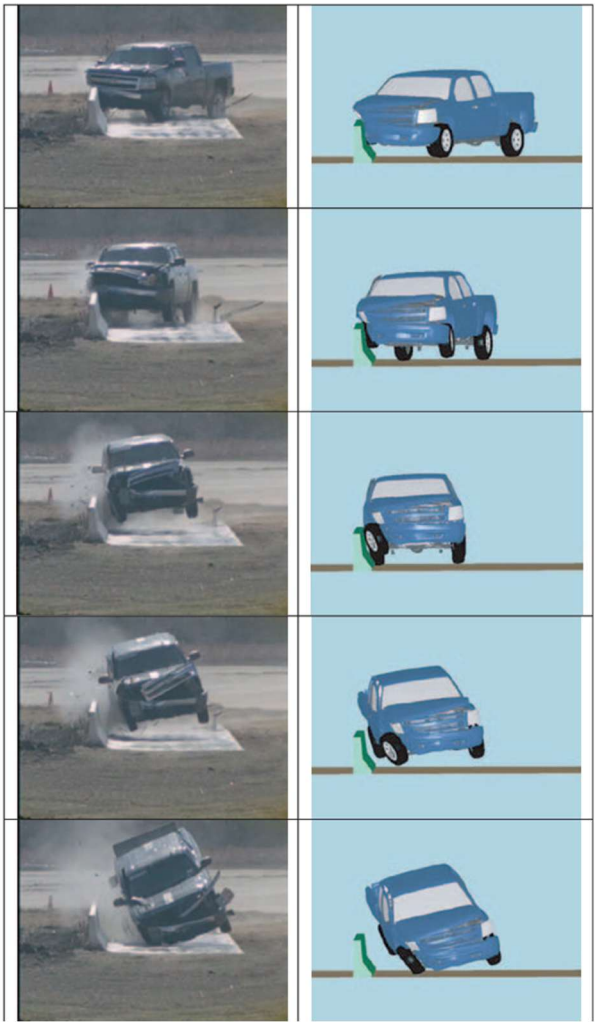

Figure 2. Sequential comparison of the full-scale crash test and finite-element simulation for a Chevrolet Silverado impacting a New Jersey barrier[18].

Concrete modeling is the major source of uncertainty. Studies assessing LS-DYNA concrete models for high containment barriers have shown that the choice of constitutive law, erosion criteria, strain rate effect, element size and parameters tuning can have a substantial influence on predicted cracking and failure [21]. Model tuning must use wherever possible experimental data and erosion must not be used to remove distorted elements without proving the associated mass loss and strength reduction physically reasonable.

Vehicle models are the second major source of uncertainty. Vehicle mass and center of gravity can be adjusted to match the test vehicle, but these must maintain inertial characteristics and suspension behavior. Tire contact, steering, cargo model and initial roll or pitching may influence truck stability. Barrier and supporting deck boundary conditions must match the tested installation and not ideal fixed foundation unless this assumption is proven [18, 21-22].

The optimal procedure is the iterative one: perform preliminary analysis to identify critical configurations and instrumentations; conduct the corresponding full-scale test; validate the model against multiple measured responses; and use the validated model for further parametric variations. The role of simulation is to extend the information obtained during testing, not to turn the unverified model into compliance evidence.

8 MASH Compliance of Different Concrete Barrier Profiles

From the review of available studies, one may conclude that there is no profile which can be termed as compliant in abstract terms. Compliance relates to a specific system having a certain height, reinforcement, restraint, length and set of attachments. However, several trends can be revealed from the reviewed studies. Well-designed and sufficiently tall single-slope barriers are known to successfully behave according to TL-4 standards. Earlier barriers, according to the review of existing studies, have been found to lack sufficient height and vehicle stability [5-6,23].

Safety shape barriers had been used successfully in the past meeting older standards and can still be used if their design, height and fixation correspond to requirements. Increased TL-4 severity implies that an old result provided by NCHRP Report 350 should not be automatically applied but verified with consideration of new parameters, including the vehicle weight, vehicle speed, rail height and installation [1-3,5-6,22].

The rails with vertical or open sides are able to provide higher level of containment if designed to be tall enough and continuous. It has been proven recently by the experiments carried out with precast and open concrete railing systems designed with connection and openings to be considered in the total design [17,24]. These results should not be generalized onto similar-looking rails without

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verifying their design regarding snagging and structural resistance.

Some special rail profiles require special consideration related to the feature of a profile that makes it special. Flared barriers are characterized by changed effective approach geometry and need to be checked via MASH tests [10]. The same can be said about top-mounted fences and glare-screen systems where both structural attachment and vehicle interaction should be taken into account [11,25]. Recycling, fiber reinforcement, UHPC, GFRP reinforcement and rubberization can help with achieving some structural or durability advantages, but crashworthiness of the system will still depend on its tested or validated configuration [27-29,31]. (see Figure 3).

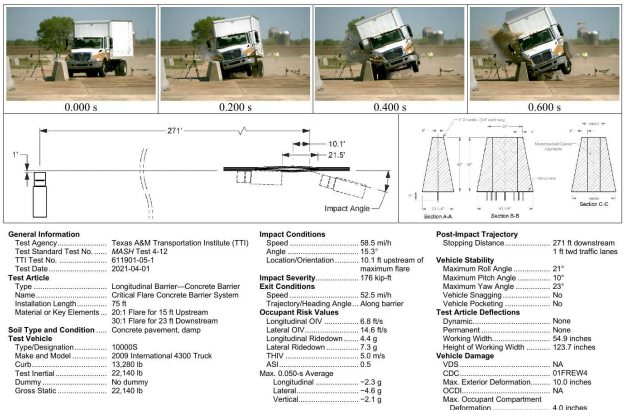

Figure 3. Summary of MASH Test 4-12 on the critical-flare concrete barrier system [10].

Analytical screening can help to find those systems that definitely do or definitely do not meet the criteria of acceptable demand. However, borderline systems need additional verification. Frameworks proposed by Hovde for evaluation of such systems and later design synthesis give rational grounds for comparison of untested permanent barriers with tested reference systems [6-7]. This approach is the most reliable if geometry and boundary conditions are close, structural capacity is proved for all modes and vehicle interaction is not affected by profile discontinuities and fixation.

Therefore, MASH compliance should be stated in one of the following ways: confirmed with applicable full-scale tests, supported for limited variation with engineering equivalence and validated analysis or not established. This terminology will prevent the case of confusion between structural adequacy and crash test approval.

9 Knowledge Gaps and Research Needs

The first important knowledge gap is the lack of common measures to quantify barrier damage and displacement. Although many studies describe the test outcome and vehicle behavior, most give very little quantitative information about crack width, spalling, residual offset, connection distress, or post-impact capacity. Commonly defined damage measures would facilitate comparison between barrier types and decision-making related to repair and continued use.

Another knowledge gap is impact force characterization. Values of peak force at different sensor positions, numerical contact forces, or filtered contact force are treated as if they represent the same physical quantity. Future studies should provide information on the type of force being measured, sampling frequency, filtering method or cut-off frequency, contact duration, impulse, load height and distribution. The base shear and bending moment should be clearly separated from the local contact force and from equivalent static load [7-9,18].

Thirdly, validation of concrete damage and failure in numerical models should be improved. Current literature demonstrates the ability of LS-DYNA to predict general vehicle-barrier interaction but prediction of cracking, spalling, reinforcement yielding and punching shear is highly sensitive to material properties, finite element mesh, contact model and erosion model [18-21]. More robust validation should include blind prediction and cross-validation using several independent tests instead of single test calibration.

The importance of foundation and supporting structure needs wider attention. The permanent median barriers may be cast in place, connected to the slab, supported by a bridge deck or close to retaining walls and grade separations. Flexibility of foundation or soil layer changes effective restraint, participating length and displacement regardless of barrier section used. System-level approach should consider vehicle impact, barrier reaction and deformation of support structures rather than unrealistic prescribed boundary conditions.

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The residual performance of a barrier after the first impact is also not well understood. Even if a barrier is standing after the impact, its stiffness and capacity could be reduced due to crack development, yield of reinforcement, damaged connections or movement of foundation. Sequence impact studies and controlled residual capacity tests are necessary to establish replacement criteria beyond visual inspection.

Finally, it is necessary to formulate performance based connection between full scale test and design calculations. A single test can cover only particular set of parameters such as barrier height and profile, details of the deck or material properties and unlimited extrapolation of numerical simulation results is not justified. Therefore, the framework for acceptable and unacceptable variations should be developed [6-7,21,30].

10 Conclusions

The performance of permanent concrete median barriers needs to be assessed as a vehicle-barrier-support coupled system. Profile determines the order of wheel and body contact; height – stability of the heavy vehicles and chance of vehicle's overcoming. Reinforcement, concrete material properties, continuity, and foundation/deck restraint determine structural damage and displacement. Any of these parameters separately does not give a complete crashworthiness characteristic.

The transition from NCHRP Report 350 TL-4 truck to MASH condition increased the nominal severity of impact by about 56 percent [1-3,5]. Therefore, historical acceptance according to NCHRP Report 350 can be considered a relevant piece of evidence, but is not sufficient demonstration of MASH TL-4 crashworthiness. Systems should be reevaluated taking into account vehicle mass and speed, effective height, profile, anchorage, and support conditions.

Damaged barrier shows flexural cracking, localized crushing and spalling, yielding of reinforcement, punching shear, joint opening, anchorage distress and deformation of support structure. Triangular yield-line mechanism may be conservative and not reflect real crack patterns, while modified mechanisms and punching shear checks are more comprehensive structural evaluation [8]. Static resistance tests are useful in identifying these mechanisms, but cannot replace crashworthiness assessment of the system.

Impact force must not be substituted with undocumented peak force. The force of contact, filtered force, support reactions, equivalent static load and capacity of the structure are different physical quantities. Comparisons must include force duration and impulse, load location and distribution, support reactions, displacement and damage of the structure. This procedure is needed in order to reconcile results of crash tests, component tests, and nonlinear structural analysis.

Full-scale testing is still the main evidence for MASH acceptance. Validated LS-DYNA model will be most useful when it reproduces several response measures and is then used in bounded parametric studies. The credibility of this model depends on the vehicle modeling, calibration of concrete and reinforcement, contact treatment, boundary conditions, mesh sensitivity, and transparent force filtering [18-21].

The collected evidence suggests a tiered acceptance procedure. Direct full-scale testing is recommended for new systems or changes in existing systems affecting vehicle's interaction with the barrier. Engineering equivalency assessment and validated analysis can justify limited variations in case of similar controlling geometry, load path and failure modes. Structural adequacy calculation without evidence on vehicle's behavior needs to be presented as screening analysis, not as MASH acceptance. Progress in the future will depend on standardized damage classification, force definition, improved concrete failure validation and clear limitation on the use of test results for related permanent barriers.

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