Development of a disruptive semitrailer tractor in light-weight construction

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1. Motivation

The most widely used supporting structure in truck design today is the ladder-type frame. This principle offers many advantages and meets requirements outstandingly, particularly at the beginning of truck development. Aside from the big payload, the concept is simple and robust while enabling a high degree of variability, usually in combination with a modular system. The relatively low torsional rigidity around the vehicle’s longitudinal axis (by comparison with a body) is an advantage in what was previously a frequent type of deployment, namely operation on uneven, unpaved surfaces.

Over the course of well over a century of development, however, design engineers have had to rise to the challenge of a great many changes in their market. To name just the most important changes, these include more drive power, more stringent emission standards with simultaneous prevention of CO₂, more complex and highly variable vehicle systems for a variety of transport tasks, more volume and comfort in the driver’s cab and specialisation in long-haul transport on predominantly smooth roads.

In consequence, different boundary conditions for the further development of the vehicle have defined themselves. Just for example, continually increased mileage and enhanced equipment with simultaneously reduced energy demands and improved environmental balance. The potential for optimisation here is mainly in the areas of energy management, driving strategy, driving resistances and lightweight construction. The lightweight construction area is under extreme cost pressure, especially in the commercial vehicles sector where the relatively low volumes are problematic. As a result, developments in this direction require significant resources because cost-effective lightweight construction is difficult to achieve by implementing isolated measures.

A further reason is directly related to ladder frames:

an additional consequence of the changes in the market is that the installation space available for the ladder frame has become severely restricted in all spatial directions. Given the inflexible ladder-frame concept, it was not possible to adapt the vehicle architecture to any significant extent. A consequence of the current frame concept for modern trucks is that developers are
forced to make considerable compromises in defining installation space and in the subsequently achievable mechanical properties of the ladder frames. These compromises have an impact on the potential of existing components to be constructed in lightweight design and on the consequent costs. Similar constraints led to passenger cars being produced with self-supporting bodies from around 1930 and buses and coaches from around 1954. However, significantly higher requirements with respect to product variability and to the associated logistics and production have until now hindered any similar development from taking place in trucks. However, thanks to the growing CO₂ debate, alternative drive concepts for trucks are again being more sharply focused on. This development has brought to the fore an advantage of the body concept that until now has not been given much attention in the sector: the gain of previously unusable installation space. The assignment of the research vehicle presented here is to demonstrate the magnitude of existing potential in lightweight construction and the gain in installation space on a semitrailer tractor with a short wheelbase.

2.0 Reference vehicle and target characteristics

2.1 Reference vehicle

Preliminary studies regarding the potential of lightweight construction of ladder frames indicated to MAN Research that we would have to abandon the current installation space of the frame in order to achieve the necessary improvement in dead weight. Seen together with the general changes in market conditions outlined in the introduction, the time had come for the structuring of a vehicle with a new vehicle architecture. The Research Department decided on a semitrailer tractor with equipment that is typical in long-haul transport as a reference vehicle. Additional air suspension on the front axle makes for better comparison of later measurements with the new vehicle architecture.
Reference vehicle: 18-tonne semitrailer tractor for long-haul transport

The cab, in its original location with mount, and the diesel driveline with engine and automatic gearbox were adopted from series production. Although the supporting structure is predestined mainly for future vehicle concepts with alternative drive systems, fundamental feasibility can also be demonstrated with the classic configuration. Because of the current situation with regard to entering the cab, the location of the front axle was also not changed. In principle, however, our vehicle concept makes it possible to relocate the front axle approximately 600 mm further forward. To improve the axle-load distribution, the driveline was moved backwards and downwards so that the cooling air-flow can also be optimised, which will in turn make smaller cooling surfaces possible. Although the vehicle's dimensions remain unchanged with a wheelbase of 3,600 mm, the supporting structure ends approximately 250 mm behind the two-bellow air suspension on the rear axle that enables this construction.

The aim of building a research vehicle that has a considerably more rigid supporting structure was to study and evaluate additional potential in handling and comfort as well as conceptual lightweight construction with a simultaneous gain in installation space. The first installation-space concepts already made it clear that independent wheel suspension and rack-and-pinion steering on the front axle exhibited advantages in terms of installation space, with additional potential as positive influences on handling. Prototypes are fitted with rack-and-pinion steering and independent wheel suspension.

The freed-up installation space is to be used to demonstrate possible improvements to the front of the vehicle in the area of active and passive safety.
2.2 Characteristics of the reference vehicle

Standard evaluations are undertaken of the rigidity, characteristics and damage (operational stability) of the primary supporting structure, the ladder frame, for commercial trucks of between 8 and 40 t gross weight. Various design-relevant parameters are thereby derived and stored in a database together with the field experience for the respective vehicles. These data are updated over the term of the vehicle series and used as the basis for new designs. Such data include rigidity values such as deformations under standardised load conditions. These are derived from the natural modes of the ladder frame. The ladder frame consists of two longitudinal U-beams connected by cross members.
In addition to the form of the side members with their offsets due to the installation space, various main dimensions of the U-beam and wall thickness are used. The side members are designed for the nominal stresses for the prevailing bending moment distribution of the frame, and are therefore predominantly oriented to the load and axle load distribution of the vehicle. The side members are connected by various cross members to form the ladder frame. The vibration behaviour of the frame can be described fairly easily. Depending on the vehicle model, between 2 and max. 8 global natural modes of the ladder frame are relevant, in the case of the reference vehicle 3. These are the following, from top to bottom (with increasing frequency); the physical equivalent is shown in () in each case:

Mode 1: Bending about the vertical axis (longitudinal impact on a single wheel)
Mode 2: Torsion about the longitudinal axis (road unevenness)
Mode 3: Bending about the transverse axis (load)

In order to better illustrate the approach, let us consider the middle mode, the 1st order frame torsion, in more detail. The simplified consideration of the ladder frame using modal analysis (FEA) shows a frequency for the frame torsion of below 10 Hz, i.e. in a critical excitation range and hence very important with respect to the damage to the supporting structure. In the real complete vehicle and the virtual complete vehicle model, the frequencies are slightly lower. For a qualitative comparison at an early stage of the concepts, however, the consideration of the basic structure is sufficient. A defined excitation from the road (uneven road surface / diagonal torsion) results in an amplitude for the twist angle at the frame about the vehicle longitudinal axis, between the front axle and rear axle. Together with the wheel load difference at the four wheels, this gives us a rigidity value as a moment per twist angle (normally expressed in kNm/rad). For the further
consideration, not only the absolute value but also the gradient of the twist angle over the vehicle longitudinal axis is of interest. The value also depends on the vehicle variant and the suspension, as primary suspension and torsion rate of the frame interact.

natural modes       Equivalent       Damage calculation
load case

For a clearer representation, attachments and cross members or brackets have been hidden in the area of the front axle.

By means of measurements at the vehicle with different operating conditions and transport applications, collectives for the respective load type are derived and validated experimentally. This is necessary in order to avert damage to the primary structure of the frame over the vehicle service life. Due to the simple relationships with the ladder frame, tests on 4-posters, normally used in the passenger car sector, are generally not necessary.

Due to the extreme variation in the operating spectra for commercial vehicles, however, a fatigue-proof design of the primary structure of the frame is economically expedient only for the majority of the vehicles (approx. 95%). The other vehicle applications are designed for specific periods of operation, and thus result in a reduced operating life.
The figures show measurement data for determining the collectives for the frame torsion, the corresponding quasi-static test stand and examples of damage to the components.

In the case of passenger cars, the chassis is generally designed on the basis of criteria of rigidity and comfort (vibration behaviour in admissible frequency ranges). Additional measures to ensure operational stability are necessary only at a small number of points (e.g. shock absorber domes on front and rear axles or load transmission at the interface between chassis and car body, etc.). Crash scenarios primarily dictate the dimensioning of the strength of the body main structure. This applies essentially to the closed design of passenger cars.

2.3 Target characteristics of the research vehicle

The main goal in the development of the present frame concept is to significantly modify the mechanical characteristics and to make optimum use of the available installation space. Modifications to the vehicle architecture are necessary for this. As with the vehicle body concept for passenger cars and buses/coaches, lightweight construction is also systematically created as a side-effect. As with passenger cars and buses, however, this is not the driving force behind the change of technology. In the present case, installation space is to be generated. This wish, in conjunction with alternative drive systems, particularly with the current voluminous energy storage systems for e-mobility, is the main motivation for the project.

A further positive side-effect is that the vehicle can be more specifically configured, while the handling and comfort of the vehicle can be significantly improved.

In concrete terms this means for our research vehicle a gain in installation space of > 1 m³. In order to increase the operational stability of the frame structure in the direction of the passenger car at the same time, the frequency for the torsional vibration should be increased from
below 10 Hz (currently 8.2 Hz) to roughly 25 Hz. In the first step, the bending about the transverse axis is not to be actively changed, as this is not expected to cause any damage. The preliminary considerations indicate that subordinate importance is also to be expected for the vibration pattern "bending about the transverse axis". This assessment must, however, be constantly reviewed. In addition, new and additional vibration patterns must be evaluated from the outset with respect to their hazard potential.

3.0 Development of a vehicle concept to achieve the objectives

3.1 Simulation process and design

Experience in designing trucks with ladder frames cannot be applied to body concepts. With the help of some preliminary tests and multibody simulations, it was possible to estimate the effect of a substantially stiffer frame system on running-gear forces beforehand, both experimentally and mathematically. For this purpose a series-production frame was globally stiffened using a bearer system. The loads for deployment in long-haul and distribution transport increase only minimally, which allows the use of corresponding near-series running-gear components in the initial approach. For the FE analyses of the concepts, a simplified method of static and dynamic stresses was used, the same as in the early concept phase of coach design. Moreover, in this vehicle segment, the running gear and the rigidities exhibited in the floor structure are comparable.

Installation-space models for topology optimisation are derived from the adequately detailed package models for vehicle architecture. The method is then applied - with varying boundary conditions - to manufacturing restrictions. The geometry is defined by calculation in several steps with manual control taking place between steps. Processing in this phase requires skills in the disciplines of design and simulation, preferably combined in individual persons.
Interim results of topology optimisation of the complete supporting structure

Of central importance in conceptualisation is the earliest possible use of simulation methods: in our case, they were already applied to the structures from topology optimisation. The mechanical properties of the smoothed geometry are checked using FEA directly and without complex reduction into CAD. Besides static rigidities and eigenvalues, only nominal stresses are checked. In this way, fewer resources are invested in the detailing of designs that hold little promise of success.

The concepts or designs for supporting structures generated here are given corresponding version numbers depending on the package status within the different virtual concept vehicles. In our case these represent different drive concepts. This means that it is possible to find many concepts that are equally worth following and with which the target values being aimed at are achievable. This modus operandi gives rise to a database with many and various solution approaches to manufacturing and production – an ideal pool of pre-development projects.
Flow chart of simulation process

design concept support structure

structure and administration package – models (CAD)

space model released

topology-optimization global partially

FEA simplified stiffness, eigenvalue, nominal stress

manual intervention for optimization process about
- interim result (iterations)
- production-parameter
- space modifications and management
- reduction in complexity

No

target value achieved?

Yes

no CAD-geometrie concept database released and grouped

Design
3.2 Concept selection, degree of detail and verification by calculation

For the prioritised tasks of building a research vehicle and clarifying feasibility, the solution approaches selected were primarily those that are linked with sound manufacturing know-how. The approach finally chosen was one that combined locally reinforced tubular segments and sandwich structures with insert components. In this context, extensive development parameters are available to us, especially with regard to our own prototype construction. Further processing and detailing of the design were carried out using CAD as the master system. This also makes it easier to apply a standardised process in verification by calculation. Besides the local verification of structural strength, a simplified examination of fatigue strength also takes place here. Target values for rigidity and eigenvalues continue to be checked here, as does the weight balance. The project was completely processed in an agile manner by a small team possessing all the requisite skills. We were able to use this to our advantage to detail the entire supporting structure from individual cells and then complete it seamlessly. In concrete terms this means that individual areas for which the environmental geometry had already been set down were initially detailed and parallel to this were also constructed as segments, while other areas were kept less structured and thus variable. The consequence of this method is that one achieves one’s goal very quickly but that the big picture only crystallises little by little. Put another way: it emerges only during processing. With respect to achieving the target values and the ongoing FEA, this represents a challenge only to a limited degree, in that the influence on global properties by local changes is not significant. Valuable development time can thus be saved, especially in the manufacturing area. An additional positive side-effect is the rising learning curve and with it, engineering designs that become increasingly viable. This processing phase saw continued and extensive use of local topology optimisation. Over long phases, the FE models for verification consisted of hybrid structures, for which a good networking strategy and standards are a prerequisite. Development and manufacture or assembly were thus parallel activities; this also applies to the complete vehicle body and the cable routing.

4. Prototype construction

As already mentioned, in the case under discussion, a chronological separation of development, prototype construction and assembly of the complete vehicle was not possible.
Nevertheless, this is an attempt to provide a cohesive description of the contents of the phase dealing purely with construction and assembly. This must be understood in the context of the development method described.

As elements of the supporting structure, open and closed semi-finished materials, flat or simply formed lasered sheets and solid components machined from full material were used. The components were connected to one another using manual MAG welding. Construction was performed on assembly bases in combination with existing jigs and angle brackets. With few exceptions, manufacturing utilised comparatively simple manufacturing machinery. The evolutionary method resulted in the emergence of a main front segment and a main rear segment, into each of which as many functions and adapters as possible could be integrated. For process-related reasons, certain segments were also formed, constructed separately and joined to the main structure using bolted connections. The interface between the two main segments was additionally influenced by production-related parameters, in this specific case by the size of the dipping plant available for cathodic dip coating (KTL). Arising from the concept, this also serves to indicate a possible modularisation of several vehicle derivatives within a vehicle group. In the event of commercialisation, the current interface would be relocated elsewhere.

Exploded view of the supporting frame segments

For optimal coating of the segments the dipping plant, simulations of the dipping process and wetting were run continually.
5. Complete vehicle and results

The initial measurement result showed a weight saving of 400 kg for the supporting structure with top coating. As expected, deviations from the CAD model were slight - under 2 kg, despite manual welding and painting.

During development, an attempt was also made to simplify the arrangement and connection of the units (control units, valves, compressed-air tanks and so on) by means of optimised cabling and piping. In the braking system, for example, it was possible to eliminate several metres of cable and air piping.

The remainder of the complete vehicle construction may be described as unproblematic, which more than justifies the great amount of effort put into the package models (largely complete and with a high degree of detail).

The complete vehicle in a roadworthy state has a dead weight < 6,000 kg, which translates to a weight saving of up to 1,300 kg or at least 1,100 kg, depending on the running gear and tyre variants.

The weight saving forecast was a minimum of 1,000 kg. It was exceeded because of the many small parts, which were difficult to calculate in advance, and because the masses of some of the new prototype units were not available beforehand.

Besides the 400 kg saved on the supporting structure, 250 kg were saved by measures taken on the rear axle, 200 kg on the rest of the driveline and 150 kg on the front axle and steering. The remaining 300 kg result from the modified vehicle architecture and overall concept.

A further, highly important result is the gain in installation space of approximately a cubic metre. Even on the prototype this could be used to realise a tank with a volume of roughly 1,300 litres. In our opinion, the additional installation space is the biggest advantage of this concept for future vehicles with electrical drivelines and alternative drive systems.

As of now, our assumption is that a dead weight of < 5.3 t can be achieved for semitrailer tractor applications where weight is an important factor. With the usual long-haul equipment this would mean a dead weight of around 5.8 t, in each case with a conventional diesel driveline.

With a factor of 5 to 20, the rigidity values are significantly higher than those of the comparison vehicle, as are the relevant natural modes, by a factor of 1.7 to 2.5.
First-order torsion around the vehicle’s longitudinal axis

6. Start-up and testing

The research vehicle was registered as a test vehicle. Complete homologation was required for the new rack-and-pinion steering.

This also applied to the brake system due to the wide-ranging modifications in the installation. However, homologation was unproblematic in both cases. Agreements were defined for each of the components relevant to safety, optionally together with the respective supplier. The agreements include separate inspection and replacement intervals.

No separate insulation measures were necessary for the acoustic test despite the relatively open framework construction in the area of the engine and gearbox. This shows that excellent values for sound emission could be achieved with comparatively little effort.

Appropriate adjustments to the running gear air suspension were needed. Good tuning was very quickly realised with minor measures. There is still more potential, which will be tapped in the course of follow-up projects.

Numerous measuring runs were carried out on various test tracks with different variants of running gear, above all with changes to the roll rate. Somewhat more extensive tuning was needed because the greatest stiffening by contrast with the ladder frame was reached here. Moreover, different tyre variants were assessed, including single tyres on the rear axle. These are necessary on vehicles that react sensitively to weight and on vehicles equipped with electrical drivelines, for example e-axles.
7. Summary and outlook

With the research vehicle under discussion it proved possible to generate a product idea outstandingly capable of taking into consideration both the current boundary conditions and the future developments necessary to the truck market.

We were also able to verify the feasibility of this vehicle idea by experiment. A paradigm change - state of the art for passenger cars and buses/coaches since the beginning and middle of the last century respectively - is thus also sensible and possible for trucks. Because construction is comparable, advanced projects will be able to draw on a state of the art with already proven and highly developed know-how from the field of body construction. However, the specific boundary conditions and target values must be taken into account here.

Relative to the prototypical implementation, there is thus further potential for structural optimisation and lightweight construction.

From our point of view the biggest challenge lies in replacing the product structure of trucks with ladder frames, which has been cultivated for over one hundred years and has seen disproportionately high growth. We believe that it is both sensible and necessary to take a completely new type of approach in order to realise modularisation for the product variance that is essential.

To this end, MAN has already been deliberating ways in which the conceptual potential of the product idea can be fittingly unlocked, also in the areas of logistics and production. The construction principle can be applied to vehicles for distribution and long-haul transport. Consequently, municipal and construction-site vehicles that operate to only a small extent on poor surfaces, at least in highly developed countries, are also conceivable. As far as off-road vehicles, WorldWide construction-site vehicles and high-mobility vehicles are concerned, our experience indicates that the ladder frame remains the better supporting structure for trucks.