INDUSTRIAL FORKLIFT TRUCKS - DYNAMIC STABILITY AND THE DESIGN OF SAFE LOGISTICS

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ABSTRACT

Forklift trucks represent a well-known occupational hazard in many modern industrial environments. In terms of severe work-related injuries and fatalities, exposure to forklift trucks in the transport industry, in wholesale and retail and in manufacturing implies high risks to operators, pedestrian workers and others in the environment. Creating industrial environments where vehicle, pedestrian and material movements can flow productively without hazardous conflicts requires logistics and safety analyses as a basis for the design and layout of facilities.

Monash University Accident Research Centre, funded by Worksafe Victoria (the local workers’ compensation insurer and industrial safety regulator), has coordinated a development project with the following components:

- the development and testing of a paradigm for dynamic stability assessment of industrial forklift trucks;
- the formation of a local team of experts in forklift safety, transport, logistics, and industrial architecture/design to develop, through a series of workshops, the details of safe forklift transport systems operationalized into "blueprint" format for a freight terminal and a warehouse, including relevant goods receiving and dispatch areas;
- a warehouse management software application, incorporating features for conflict prognosis and necessary parameters for the managing of a distribution centre;

The project has also analysed existing alert, proximity warning and navigational systems, including systems based on ultraviolet, microwave and laser technology, together with several applications of speed limiting technology, and developed and tested a prototype RF-tag and on-vehicle receiver unit to assess costs and feasibility of using radio frequency technology to identify pedestrians in forklift truck zones.

Testing of different combinations of electronic control devices for on-vehicle or other traffic management applications for industrial forklift trucks is undertaken at a number of industrial "testbed" locations.

The blueprint designs will be used in a planned subsidy program targeting existing and prospective medium-size transport terminal operators in Victoria, where Worksafe Victoria covers the cost of expert
assistance in translating the blueprint to the specific requirements of an operator willing to use the design as the basis for their new or upgraded facility.

The development project aims to report its findings in the form of a "Safe Forklift Management Manual", the main focus of which is the safe management of the forklift transport system, with basic parameters such as rational logistics, good information ergonomics, optimal traffic separation and management, speed and proximity control, well-structured operational environments, good systems management and preferred secondary vehicle safety features.

1. BACKGROUND

Forklift trucks represent a well-known occupational hazard in many modern industrial environments. In terms of work-related fatalities, exposure to forklift trucks in the transport industry, in wholesale and retail, and in manufacturing, carries a high risk to operators, pedestrian workers and others in the environment (Collins et al, 1999a;b;c).

During the period 1989 to 1992 one Australian worker was killed by a forklift truck every month. A large proportion of the fatalities were in transport/storage and wholesale/retail (42%), but manufacturing (32%), agriculture (12%), construction (8%) and mining (4%) also suffered substantial numbers of forklift related fatalities (NOHSC, 1998).

A study of forklift trucks and severe injuries in Victoria 1987-1990, reported that this State contributed 15 fatalities to the Australian forklift death toll over a period of 30 months. Forty-two percent of the surviving injury victims were off work for more than 2 months (Larsson & Rechnitzer, 1994).

Recent data from the Victorian workers’ compensation system indicate that hazards and injury problems related to forklifts have changed only marginally in the last decade. Annually, around 500 claims, 40 of which long term, and 2 fatalities were reported in the period 1993-97. The compensation cost alone for forklift related claims in Victoria during this period was $16 million per annum, where manufacturing represented 46%, trade 20% and transport/storage 23% of the claims volume (VWA, 1999).

1.1 Conceptual development of facilities and vehicles

From earlier research it is clear that most forklift transport management suffer from the major shortcoming of not defining the forklift truck as a vehicle requiring systematic traffic management in the working environment (Larsson & Rechnitzer, 1994). As the forklift truck becomes more versatile and flexible in its industrial use, the need to restrict, control and manage this physical hazard in the working environment increases. The crucial variables are stability, speed and proximity to pedestrians.

Stability represents a key variable in the design of safe counterbalance forklift truck logistics. The project has sought to develop a dynamic stability testing paradigm which has been applied to one 1.8 tonne and one 2.5 tonne counterbalance forklift truck and to a 2.0 tonne counterbalance forklift reach truck/stacker. The project also sought to address the issue of optimal location of stability sensors and the stability aspects to be covered (load mass, load position, load balance, load height, mast tilt, etc).

Forklift speed represents a major occupational hazard. Whilst not always specifically identified in the reported forklift related fatalities, major operators identify speed as a concern in relation to forklift truck incidents and forklift related trauma. Some current speed control systems are based upon engine power governors. Whilst slowing the travelling speed, these also rob the forklift of much of its operating power for raising and lowering loads. Some engine governors are also easy to tamper with.

Relevant principles of traffic safety and information ergonomics should obviously be applied to the areas of logistics and transport management design. The insights and developments within the new field of Intelligent Transport Systems (ITS) and its possible applications into industrial environments can improve forklift truck management. Electronic proximity control, with designated vehicles, speed zoning, alerts on blind corners and recognition of pedestrian workers, would reduce hazards and avoid collisions on industrial sites, but also generate further benefits from improved logistics, i.e. control of vehicle use, vehicle users and cargo movement.
This project aims to define safe forklift environments and to produce architecture/design blueprints, where systems and logistics parameters are clarified, and the principles of safe forklift operations described. The necessary applications of available technology for speed and proximity control devices in order to facilitate retro-fit into older vehicles and existing industrial layouts will be trialled in testbed facilities together with industrial partners and with the help of logistics and safety experts.

2. PROJECT ACTIVITIES

2.1 Stability criteria

In the design of equipment and vehicles it is common to use safety factors to ensure that dynamic effects and wear do not compromise the safety of structures in use. Building crane structures typically have a safety factor of around 6 - that is they are designed to withstand 6 times the rated lifting load – and chains and slings have a safety factor of around 4. Heavy trucks have safety factors of 3.5 - 5.0 in relation to vertical loads, and trailers a safety factor of 2.5. Chains and webbing used to restrain loads on trucks have safety factors around 2.0.

Engineering safety principles in relation to the stability of counterbalance forklift trucks are expressed in the testing regime prescribed by the ISO Standards, which is related to the risks of tip-overs, roll-overs, and loss of loads.

- Test 1 requires the mast to be at maximum height, and loaded with a rated load at rated distance. The forklift is then tilted forward on a tilt frame to a slope of 3.5% o 4% (2.0 - 2.3 degrees). This is equivalent to moving the rated load about 160 mm - 200 mm away from the mast towards the end of the fork tines.
- This increases the distance from the load to the front wheels, so that the forklift is more likely to tip-over.
- This may determine the maximum load to avoid tip-over.

- Test 2 requires the forks to be lowered with a rated load at rated distance. The forklift is then tilted forward to a slope of 18%. This is equivalent to moving the rated load about 90 mm further away from the face of the forks.
- This may determine the maximum load to avoid tip-over.
• Test 3 requires the mast to be at maximum height and at full rearward tilt, and the forklift loaded with a rated load at rated distance. The forklift is positioned at a defined angle across a tilting platform, and the platform is tilted to a slope of 6%.
• This may determine the maximum load to avoid roll-over.

• Test 4 requires the mast to be lowered and at full rearward tilt, and the forklift unladen. The forklift is positioned at a defined angle across a tilting platform, is then the platform is tilted to a slope of up to 57%.
• This may determine the maximum resistance to roll-over when empty.

Test 3 above according to the ISO Standard accepts a static criteria situation with a safety margin of virtually zero.

2.2 Testing dynamic stability

Four configurations were simulated. In all cases the mast was vertical:

• Case A - rated load and rated distance - equivalent to a uniform 1200 mm cube weighing 2090 kg;
• Case B - 50% of rated load at rated distance - equivalent to a uniform 1200 mm cube weighing 2090 kg;
• Case C - two uniform 1200 mm cubes weighing 1045 kg stacked on top of each other; and
• Case D - two uniform 1200 mm cubes weighing 1045 kg stacked on in front of each other on extended forks.

As a result of the rating method for forklifts using AS 2359 (or the equivalent ISO standard), counterbalance trucks may have zero safety margin for one test in a static test situation. Whilst this is theoretically self-evident it is not readily appreciated until testing is undertaken.

The consequence is that an operator observing plated load limits could be at great risk from dynamic effects (braking, accelerating, suddenly stopping a load being lowered, et cetera). In the testing done to date it was apparent that:

One forklift appeared to have zero margin at rated load at full forward tilt (test was stopped before the forks were at full height because weight on steer tyres was less than 100 kg;

One forklift, when loaded to rated load plus 10% appeared to have virtually no safety margin when the load was raised to full height with the mast vertical. This was the situation even though the calculated safety factor for the rated load with the forks down was about 50%. The dramatic reduction was brought about because the pneumatic tyres allowed significant forward tilting so the centre of gravity of the load moved about 250 mm forward, with the centre of gravity of the mast also moving forward.
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Pneumatic tyres allow much greater deflections than solid rubber tyres. Hence dynamic effects when being operated (versus the static situation during testing to a Standard) may be more likely to lead to stability problems where pneumatic tyres are fitted. For two near identical forklifts from a rated load point of view, the pitch angle of the pneumatic tyred unit was six times that of the solid tyre unit.

Standards may have safety factors in regard to stability that are less than zero under emergency braking or heavy acceleration. As enacted internationally, ISO 10525, which refers to additional stability tests required for travelling with a loaded container is one of these. Emergency full braking will result in a tip-over.

In testing to AS 2359 of similar ISO standards, with single drive wheel and outrigger forklift configurations, forklifts are allowed to tilt until the structure makes contact with the tilt surface. Testing may then continue until the required test angle is reached. However, in travel, if the unit tilted till the structure hit the ground, a moment would be generated that would tend to cause the unit to pivot about the point of contact. This has the possibility of making the situation worse.

Forces generated when the forks are lowered at full speed and then stopped may increase the effective load by 25%. In a critical situation this could be sufficient to initiate tip-over.

Minimum braking standards as proposed in ISO 6292, and as existing in AS 2359 are significantly lower than the minimum of about 0.35 “g” applying for road vehicles. Whilst this is not a significant problem at speeds close to walking speeds and where minimum braking is 0.15 “g” or greater, at higher speeds and/ or lower minimum braking standards the increased braking distances reflect a hazard re collisions or hitting pedestrians.
Whilst investigation and test results are preliminary, it is apparent that safety of forklifts in regard to stability very much is a rating issue – reducing the rated capacity would reduce the risks of tip-over and rollover.

Tests and dynamic modeling show that safety margins in some circumstances are low. Heavy braking in an emergency situation with full or close to full loads will easily reach imminent tip-over where the surface on which forklifts travel is not level and flat, especially when forklifts are placing or picking up loads at full height.

Tip-over risks are also high when forklifts are used at full forward tilt, when pallets are double stacked on forks to increase productivity, or when pallets are loaded to the centre of trucks.

### 2.3 Terminal and Warehouse Design Blueprints

With the help of a one-day seminar and planning session with all interested stakeholders (regulator, researchers, forklift manufacturers, transport industry parties, safety products procurers, other industry representatives) and a series of workshops with a blueprint design group, including experts in architectural design, transport, warehousing logistics, and safety, it was possible to develop:

- a basic transport terminal for cross-dock operations, including same-level forklift truck operations, as the main framework for the blueprint development,
- principles for site control, traffic and transport flows, pedestrian/vehicle separation, and forklift truck zones incorporated,
- specifically, the potential high-risk interaction between forklift trucks and truckdrivers addressed by a staging of the flow of unloading/loading activities into an untarping/preparation area (no forklifts), an unloading/loading forklift truck area with pedestrian safety islands and escape stairs to driver amenities at first floor, and a tarping/load consolidation area (no forklifts),
- a distribution centre blueprint was also developed, incorporating several of the site plan principles of the terminal, based on cross-dock split level operations,
As one output of the ongoing project, the regulator has drafted guidance material focusing on the loading and unloading of trucks, which is a documented high risk activity for anyone standing or moving around on foot near the forklift or the load. The driver standing next to a truck or on the tray of the truck during loading and unloading remains a standard industry practice. The main reason given by the industry is that the driver must ensure that the mass is distributed appropriately over the vehicle axles and ensure that the layout of the load suits the order of delivery at different locations.

The view of the regulator is that there needs to be a clear concept of what good practice looks like (legal compliance) and what poor practice looks like (non-compliance). Adopting the underlying principle that forklifts and pedestrians must be separated in space or time, the result is shown in Figure A.

While some industry operators have continued to argue that this is not practicable others have implemented the approach and even improved on it with added productivity gains. Figure B shows an example of how one operator adapted the concept of exclusion zones around three vehicles where previously there were three forklifts unloading the vehicles and three drivers standing or moving around next to their vehicles. Now only one forklift is used to unload the three vehicles, the other two forklifts remain outside the exclusion zone and shuttle freight to the warehouse. This immediately improved productivity by reducing turnaround times. However, the change could be combined with a further productivity measure, as the new traffic management practice facilitated the installing of weigh scales on the edge of the exclusion zone so that all freight could be weighed as it came off the trucks. The operator’s suspicions of systematic undercharging of cargo were confirmed; in the first shift alone approximately 12 tons of extra ‘unpaid’ freight was found.

The guidance material documents are available at


Figure A
To complement the architectural design and exemplify its dynamic properties, a warehouse management program was developed with the help of the Planimate modelling software package. The model incorporates features for conflict prognosis and all necessary parameters for managing a distribution centre, and it can be used to evaluate warehouse layout, operating strategies and to report on operational efficiency and near miss profile.

The program provides animated dynamic discrete event simulation based on queuing theory. Paths over the floor plan deal separately with different classes of mobile items (trucks, forklifts, people, etc), the program indicates one-way and two-way paths and includes an algorithm to determine the shortest route between two locations. The paths are identified by the locations at the ends of their sections, and these locations include intersections, bends, and functional locations such as unloading and loading bays.

The near miss profile is based on the time separating items passing through each location and the relative direction of the items. There is a different risk of accident if items are following the same path or on crossing paths. The time separation for each type of relative direction is reported as a distribution.

The movements into and out of the modelled zone is specified in a schedule table and the table can be populated manually or from statistical distributions. The strategies to be used for movement within the modelled zone are open for discussion.
2.5 Trials and testbed applications

The project has discussed the different levels of equipment safety required by the variations in forklift use and environments. The basic on-board and vehicle design parameters should integrate passive safety features improving the use of the forklift vehicle in all environments, including in single vehicle, small-scale operations. In such environments the likelihood of environment/facility design safety features is low due to cost/demand factors. However, integrated on-board safety features will be potentially applicable in all environments.

The project has sought to establish a number of principles and forklift vehicle safety parameters. In relation to closeness to pedestrians and co-workers, the project is investigating the feasibility to equip the forklift vehicle with **proximity controls**. Such controls must be realistically studied in terms of performance, sensitivity, range and occlusion problems, and solutions must be adapted to the specific operational environment (lighting, climate, surface, obstructions, etc). These crucial aspects of proximity control can only be evaluated in the field. The applied tests might also consider controls to be used

- in relation to certain locations (blackspots)
- in relation to other forklifts/vehicles
- in relation to forklift operator on foot

A line-of-sight contact between a fixed point in the environment (a doorway, a corner, etc) or a moving pedestrian and the forklift vehicle can be established using ultraviolet light ("AMSKAN"), microwave radio frequency (Identcode, Tagmaster) or laser (NDC, Lazerway, Sick). The restrictions are that line-of-sight might provide inadequate distance between vehicle and pedestrian at blind corners or in places where the view is blocked. Microwave frequency will not travel well through water (incl. the human body), which means that tags will require special solutions stitched into garments in order to be detected from any angle.
A simple RF-tag with a coded signal, together with a strong forklift-placed receiver has been prototyped in the project. This is an extremely cheap solution and therefore suitable for inclusion in a retrofit package, and it should be seen as an extra layer of redundancy and safety, which should operate together with vehicle/pedestrian separation and speed zoning of the facility.

The basic link between RF person detection and speed control must be integrated with sensors measuring continuous dynamic stability. The safety algorithm will ideally define and control the safe operating envelope of the forklift truck in terms of dynamic load, speed, acceleration, braking, turning circle, and provide feedback to the operator - pedestrian alert, stability alert, speed zoning alert.

The forklift safety system must represent a credible retro-fit option, which includes speed control (e.g. Mannesman VDO Kienze), dynamic stability feedback and proximity detection (RF). The system should be economically realistic to retro-fit on single vehicles and thus be independent of, but easy to combine with, fleet management and other logistics/navigational systems.

Further structural additions improving injury minimization discussed with forklift manufacturers include pressure-sensitive skirt/belt around the sides and back of forklift body, wheels caged or wheel cover designed to protect close contact with feet/legs, and forklift drivers’ seatbelt configurations linked to the operation of the truck and difficult to bypass.

2.6 Planned output

The main focus of the development project has been to upgrade transport logistics in areas of high forklift truck use and to suggest ways of integrating safety and traffic management aspects into distribution, warehousing and transport. The project will produce a "Safe Forklift Management Manual" for the management of forklift truck transport systems, with basic parameters such as rational logistics, good information ergonomics, optimal traffic separation and management, speed and proximity control, well-structured operational environments, good systems management and preferred secondary vehicle safety features. The specific applications of safe forklift transport solutions will differ between environments. A general systems manual must be supplemented with parts specifically targeting the forklift applications and problems within the transport, the wholesale/retail and the manufacturing industries.

The design blueprints will be put to use in a "new facility" Worksafe Victoria subsidy, which will cover the cost of an architectural/design consultant for one week of work ($3,500.-), applying the blueprint
model to the specific circumstances of the planned facility or facility upgrade, and to be conditional upon the participation of the recipient company, and its new facility, in any Worksafe Victoria public relations or promotional activities. A maximum of 20 companies will be included in the pilot, and the participating companies will be carefully assessed in terms of hazard levels and injury experience before and after the change.

REFERENCES


