

DESIGN OF URBAN FREIGHT VEHICLES TO MAXIMISE CAPACITY



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Abstract

Common approaches to assessing the manoeuvrability of large vehicles often fail to consider adequately the operation for which the vehicle is intended. Modelling of vehicle manoeuvrability is often limited to ‘steady state’ cornering, rather than realistic manoeuvres. An approach is presented here for assessing the maximum realistic size of a vehicle for design purposes by considering its manoeuvrability requirements in an application-specific way. GPS tracking data from in-service vehicles is used to identify a library of manoeuvres for a typical operation, and satellite views of the location used to define the outline of the manoeuvre. Vehicles of various dimensions were then simulated attempting the manoeuvre. A contour plot was generated showing what percentage of the manoeuvres any set of vehicle dimensions could succeed at. Results for a home grocery delivery operation showed scope for increasing the capacity of the vehicle without penalty to access by up to 1 m, and up to 1.5 m if the rear axle is allowed to steer.

Keywords: Manoeuvrability, Urban freight vehicles, Vehicle modelling

1. Introduction

1.1 Background

The proportion of the population living in urban areas, both in the UK and worldwide is increasing. Exact figures vary depending on the definitions, but globally more than 50% of people now live in urban areas. This is expected to rise to more than 60% by 2030, with more than 33% of people expected to live in cities with more than half a million inhabitants [1]. In the UK, the percentage of the population living in urban areas is over 80% [1].

As population density increases, it is important to reduce the number of vehicles present on the roads, so as to mitigate congestion problems, reduce noise, and reduce greenhouse and noxious gas emissions. One way to achieve this is to use the most efficient home delivery vehicles in place of personal car trips for delivery of groceries. Other examples include maximising the capacity of store restocking vehicles and refuse collection vehicles.

Efficiency of vehicles in terms of fuel economy and reducing emissions can be improved by using fewer, larger vehicles [2], which also reduces the number of vehicles on the road, reducing congestion. However, this is only possible if the larger vehicles can access the same locations as the smaller vehicles they replace.

When designing vehicles however, selection of dimensions to optimize capacity is often done without sufficient consideration for the application for which the vehicle is designed. In particular, current approaches to modelling manoeuvrability are limited to ‘steady state’ cornering, or consider transient motion in isolation, rather than as part of a realistic manoeuvre [3, 4]. An approach is presented here for generalised modelling of manoeuvrability of urban freight vehicles, to address particular classes of operations. The aim is to provide an estimate of the increase in vehicle capacity which could be achieved without compromising the access of a vehicle (the areas which the vehicle can reach). A further aim is to quantify the impact of handling interventions such as rear-axle steering on the access of the vehicle.

2. Research Approach

The approach described in this paper used GPS tracking data from in-service vehicles for a particular class of operation. This created results which were application-specific. The example presented here is home-delivery of groceries in a congested UK city, but the method can be used for other applications including re-stocking of city-centre stores, and refuse collection vehicles. The overall strategy was to generate a library of relevant, difficult manoeuvres. In this case, interviews with drivers provided the locations of the most difficult manoeuvres. Figure 1 is an example of a typical manoeuvre from a home delivery route. The approximately 90 degree left turn is complicated by parked cars and street furniture.

For each manoeuvre, the constraints on vehicle motion (such as walls, street furniture or the edge of the road) were extracted. This was done manually by taking a satellite picture of the location and drawing the edges of visible constraints on the image. A vehicle was then simulated attempting to complete the manoeuvre using an exhaustive set of possible paths and a trajectory optimization strategy. Some critical dimensions of the vehicle were then varied, and a chart plotted of the dimensions at which the vehicle could complete the manoeuvre. The charts for each manoeuvre were layered, to give a ‘percentage of manoeuvres passed’ score for any given vehicle dimensions.

The vehicle was then simulated attempting the same manoeuvres, but with rear-axle steering enabled, to allow assessment of the impact of rear-steering on acceptable vehicle dimensions. The aim was to quantify the increase in the vehicle dimensions (and therefore the increase in volume capacity) which could be made without limiting the areas which the vehicle could access.

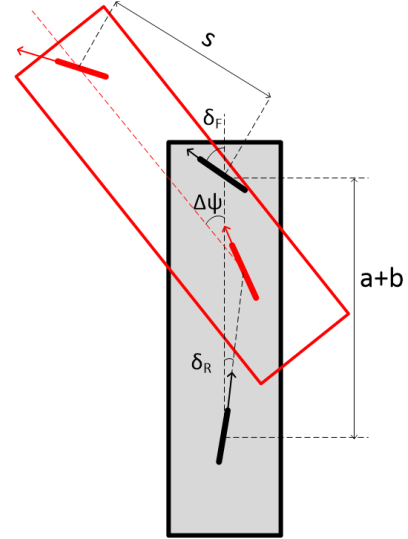


Figure 1 - Sample manoeuvre from a home delivery operation Figure 2 – Kinematic vehicle model

2.1 Vehicle Model

For all manoeuvres, the vehicle speed was assumed to be low, and the slip angles of the wheels assumed to be zero, therefore a kinematic model was used, as shown in Figure 2. The heading angle γ of the ‘lead point’ (the centre of the front axle) was determined from the yaw angle of the vehicle ψ and the steering angle δ_f .

$$\gamma = \psi + \delta_f \quad (1)$$

The vehicle speed U , and a time step Δt were fixed at 1 m/s and 1 s respectively. The lead point was moved in the direction γ by a fixed distance $s = U \cdot \Delta t$ according to

$$x_{t+1} = x_t + s \cos(\gamma) \quad (2)$$

$$y_{t+1} = y_t + s \sin(\gamma) \quad (3)$$

The yaw increment $\Delta\psi$ of the vehicle was determined from the front and rear steering angles δ_f and δ_r and the wheelbase $a+b$, and integrated to give the yaw angle according to

$$\Delta\psi = s \frac{\sin(\delta_f - \delta_r)}{l \cos \delta_r} \quad (4)$$

$$\psi_{t+1} = \psi_t + \Delta\psi \quad (5)$$

The choice of time-step Δt required compromise between the precision of a fine resolution simulation and the computational expense of running a large number of detailed simulations. The time-step used was one second, which corresponded to a distance per step of one meter. The precision of the simulation was limited by this relatively large step, but this allowed the model to run at an acceptable speed.

2.2 Control Strategy

A Model Predictive Steering Controller was designed to simulate the driver's control of the vehicle being tested. At any given position, the controller analyzed a range of steering angles, from full right-lock to left-lock. The simulated path at each steering angle was awarded a score, and the highest scoring angle was selected as the steering angle for the following time-step. This search process was then repeated at the next position.

The score awarded to the steering angle was calculated by simulating the vehicle travelling with that steering angle. At every step, a cost function was evaluated for the simulated vehicle, and added to the running total. If the simulated vehicle collided with a constraint, that steering angle ceased to be evaluated, and the score stopped accumulating. This effectively penalized steering angles which caused collision with constraints early in the path. The score for each step was scaled by an exponential 'forgetting factor' so as to prioritize the scores of points closest to the current position. The cost function increment ΔJ is given by

$$\Delta J = e^{-K_E t} (K_L d_L + K_R d_R + K_F d_F + K_P d_P) \quad (6)$$

where d_L and d_R are the distances from the lead point to the closest constraints on the left and right sides respectively, d_F is the distance from the lead point to the closest constraint ahead of the vehicle, and d_P is the distance of the lead point from the suggested nominal path. K_L , K_R , K_F and K_P are the gains on their respective observations, and K_E is the exponential gain. Figure 3 shows the parameters used for calculating the cost function.

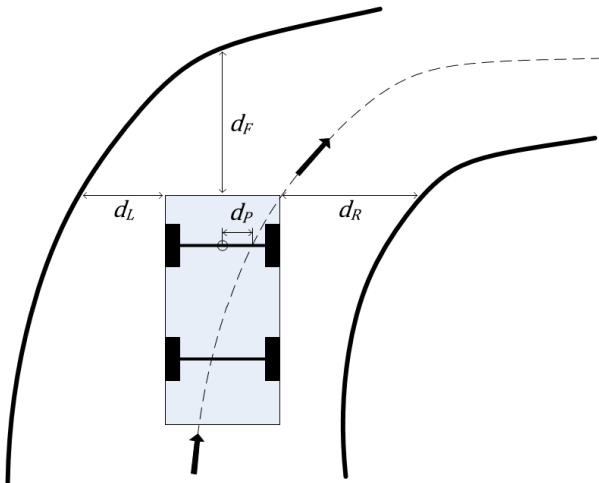


Figure 3 - Parameters used for evaluating cost function

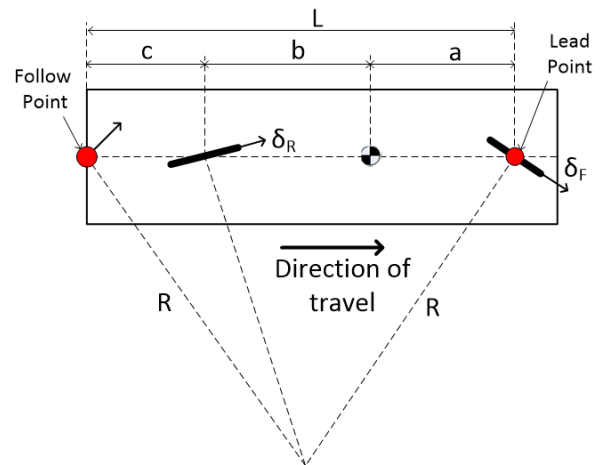


Figure 4 – Command-steer geometry

2.3 Rear Steering

The simulations were repeated with rear-axle steering enabled, to assess the impact on manoeuvrability of the rear-axle steering. 'Command steer' was used for the rear-axle control strategy [5]. The strategy calls for a rear steering angle proportional to the front steering angle. It typically reduces cut-in, but is known to increase tail-swing. The rear steering angle δ_r was

calculated to ensure that the ‘follow point’ at the rear of the vehicle followed the path of the lead point in steady state.

$$\delta_r = -\tan^{-1} \left[\frac{(a+b-c)}{(a+b+c)} \tan(\delta_f) \right] \quad (7)$$

Here $a+b$ is the wheelbase and c is the overhang of the follow point relative to the rear axle (Figure 4).

3. Results and Discussion

3.1 Conventional Vehicle

Figures 5 and 6 show respectively the largest vehicle (9 m) that can pass the example manoeuvre, and the effect of increasing the size of the vehicle past this (10m). The solid line shows the path of the lead point, and the dashed line shows the path of the rear of the vehicle. The satellite images were removed from the background of the Figures for clarity.

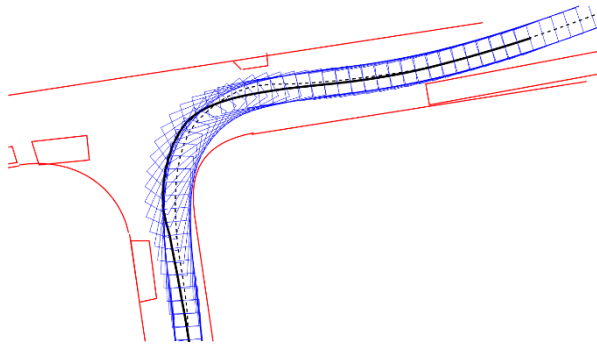


Figure 5 – 9 m long unsteered vehicle, successfully attempting the manoeuvre

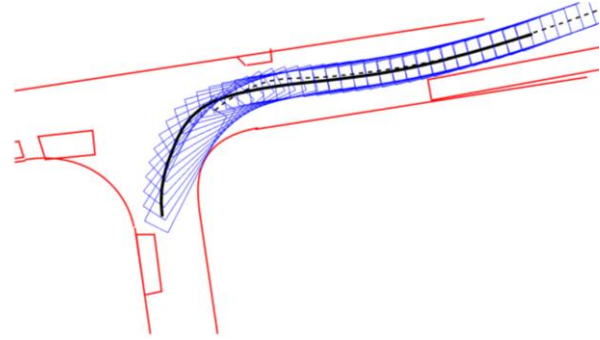


Figure 6 – 10 m long unsteered vehicle, unsuccessfully attempting the manoeuvre

Figure 7 shows the variation in success in completing the manoeuvre with different vehicle dimensions for the manoeuvre shown in Figures 1, 5 and 6. The light yellow region shows the set of feasible vehicle dimensions. The vehicle dimensions varied were the overall length of the vehicle, L , and the wheelbase, $a+b$ (see Figure 4). Some regions of the chart were removed, as these vehicle configurations are implausible. For example the top, left corner of the chart shows vehicles where the rear wheels are located past the end of the vehicle, and the bottom right shows vehicles where the overhang behind the rear wheels is greater than the length in front of the rear wheels. A simple multibody model was constructed, assuming a constant load density and similar chassis and engine parameters to an existing vehicle. This allowed the rear axle load and total vehicle mass to be calculated. Figure 8 is a contour plot, showing the percentage of manoeuvres (from the library of twelve shown in Table 1) that any given vehicle configuration was able to complete. Very small vehicles could complete 100% of the manoeuvres, while the largest vehicles had a 0% pass rate.

3.2 Command Steered Vehicle

Figures 9 and 10 show a comparison between the paths of the unsteered vehicle shown in Figure 5 and a vehicle with command steer enabled at the rear axle of the same size. The figures show the effect of adding command steer to the vehicle – the tail of the vehicle swings out much

more, which allows the front of the vehicle to pass closer to the inside of the corner (without the cut-in causing a collision) and therefore avoid the obstacles on the outside of the corner.

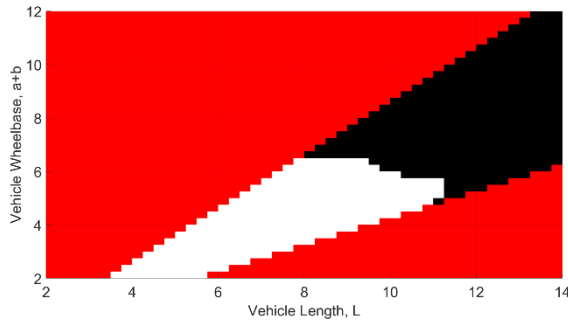


Figure 7 - Results for an unsteered vehicle attempting the first manoeuvre

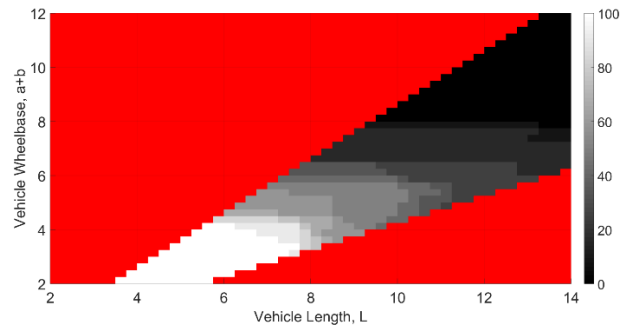


Figure 8 - Results for an unsteered vehicle across all manoeuvres

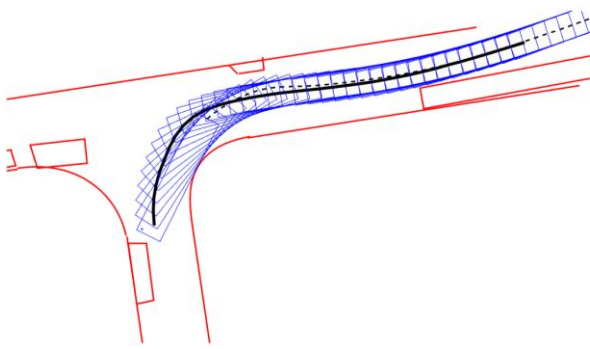


Figure 9 – 10 m long Unsteered vehicle attempting the manoeuvre unsuccessfully (identical to Figure 6)

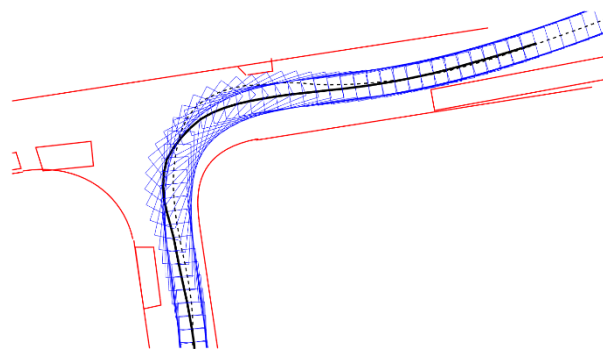


Figure 10- 10 m long Command steered vehicle completing the manoeuvre successfully

Figure 11 shows the comparison between the chart for the unsteered vehicle (solid line) and the command steered vehicle (dashed line). Figure 12 shows the amalgamation of the charts for all the manoeuvres under command steer.

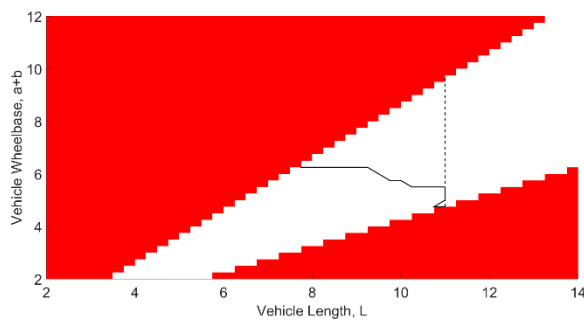


Figure 11 - Comparison between unsteered and command steered vehicles for manoeuvre 1

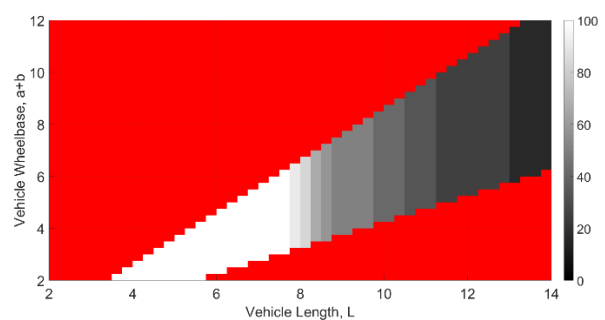


Figure 12 - Combined chart for the command steered vehicle across all manoeuvres

3.3 Effect on Axle Loads

Figure 13 shows additional constraints on the dimension space. The manoeuvreability constraints shown are for 100% pass rate, both unsteered and with command steer. Two possible Gross Vehicle Weights (GVWs) are also shown – 3.5t and 4.25t. 3.5t is the current limit, above which an HGV license is required. A proposal to raise this limit to 4.25t is under consideration. Figure 13 also shows contours of constant rear axle load. Finally, an existing 3.5t home delivery

vehicle is shown at $L = 6.25$ m, $a+b = 3.75$ m, and the rated axle load for the tyres on this vehicle is shown as a dashed line.

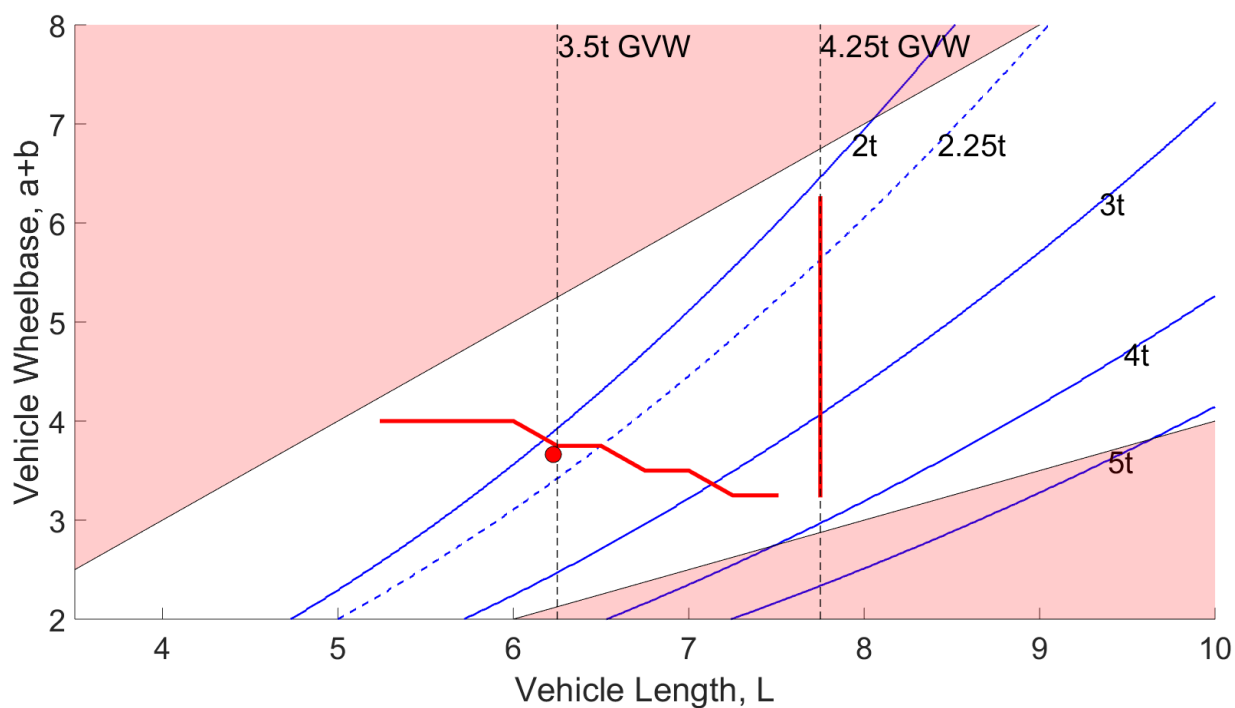


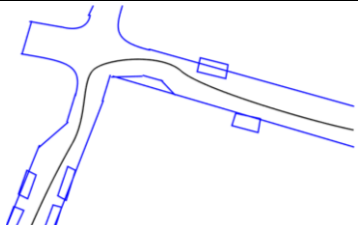
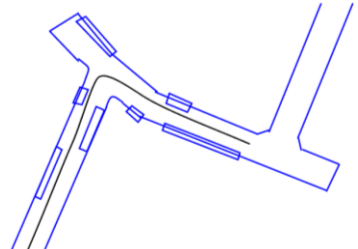
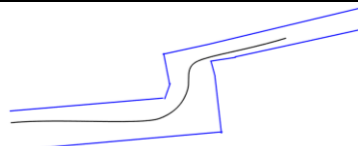
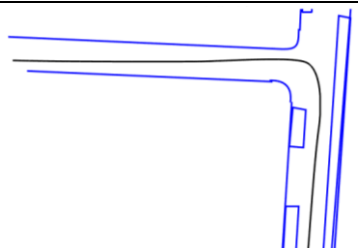
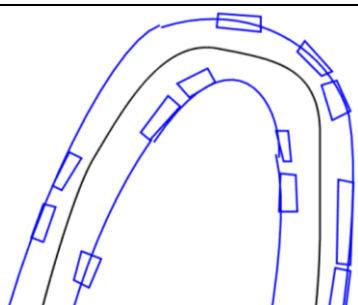
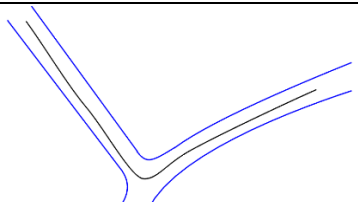
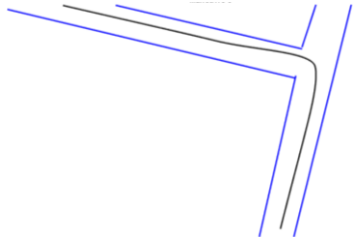
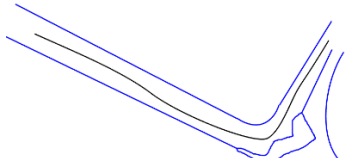
Figure 13 - Additional constraints on the dimension space

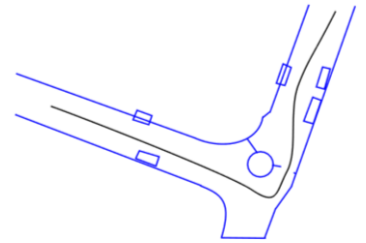
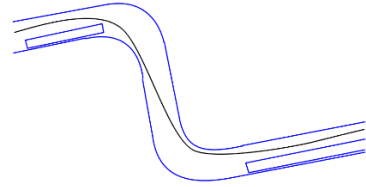
3.4 Results Summary

Table 1 shows a summary of the results across both steering options and all of the manoeuvres.

Table 1 - Summary of manoeuvre library, including lengths of largest successful vehicles

Image	Description	Vehicle Length, Unsteered (m)	Vehicle Length, Command Steered (m)
	90-degree turn	11.25	11.25
	180-degree roundabout	13.5	13.25

	90-degree turn	8.5	8.5
	135-degree turn	8.5	8.25
	Left then right turns	9.5	8.75
	90-degree turn into narrow road	8	8.25
	Elongated 180-degree turn	14	14
	90-degree turn	8	7.75
	90-degree turn out of narrow road	8	8
	90-degree turn with obstacles	14	14

	90-degree turn through narrow gap	11	10.5
	Right then left turns	10.25	9.75

3.5 Discussion

Figure 8 shows the percentage pass rates of manoeuvres across the range of vehicle dimensions. A Mercedes Sprinter vehicle commonly used for home delivery has a wheelbase of 3.75 m and a total length of 6.25 m. The chart shows that the total length of the vehicle could be increased to approximately 7.75 m without reducing the 100% manoeuvre pass rate of the existing vehicle. Assuming the size of the cab remains constant, this increase in total length corresponds to approximately 40% increase in volumetric capacity. The comparison between Figures 8 and 12 shows that implementing rear-axle steering has very little effect on the maximum length of vehicle which can pass 100% of the manoeuvres.

However, Figure 13 shows that increasing L by 1.5 m to 7.75 m for the unsteered vehicle requires reducing the wheelbase to avoid failing the most difficult manoeuvres. This causes the vehicle to cross the axle load contours, from 2.25 t to 3.5 t, which raises the size and cost of the axle significantly. With rear axle steering, the same increased L can be achieved at a wheelbase of 6 m, which keeps the axle loads at a very similar level, and still allows 100% of manoeuvres to be passed. A vehicle with $L = 7.75$ m would be likely to have a total vehicle weight of more than 3.5t, but would still remain below the 4.25t contour, so HGV licensing may still not be required.

The example application investigated in this paper was home delivery vehicles. However, the method is applicable to any vehicle and application. This research aims to address the question of the maximum feasible size of vehicles solely from the point of view of road access. There are additional factors not considered here, which might make such vehicles unsuitable. A common example is the question of licensing – increasing the size of a vehicle might take it into a higher licensing category (as is particularly the case with the home delivery application) requiring stricter driver training and greater expense. Vehicles which are already weight limited as opposed to volume limited will find no benefit from increasing volumetric capacity. Finally, there are social considerations such as safety of other road users, noise and emissions.

4. Conclusions and Further Work

4.1 Conclusions

- (I) A method was developed for assessing the manoeuvrability of vehicles, in an application-specific way. This involved modelling the vehicle attempting a library of the most difficult manoeuvres associated with the application, and assigning a percentage pass rate. Existing vehicles could then be compared to new vehicle designs.
- (II) Home delivery vehicles were investigated. It was shown that the length of a standard home delivery vehicle could be increased by approximately 1.5 m without reducing the percentage of manoeuvres it was able to complete.
- (III) The home delivery vehicle was simulated with a command-steered rear axle. This did not increase the length of the vehicle that could complete 100% of the manoeuvres further, but allowed greater freedom in the positioning of the rear axle.
- (IV) It is concluded that a substantially more productive vehicle, with up to 40% greater payload vehicle could be used on this manoeuvrability-constrained application.

4.2 Further Work

The work on home delivery vehicles will be expanded to consider alternative interventions to improve manoeuvrability, such as alternative rear-steering strategies. Applications for larger goods vehicles will be investigated, such as refuse trucks, and HGVs required to access urban areas, such as those used for restocking convenience stores. The interventions used to improve manoeuvrability may be different in this case. For example it may be useful to investigate whether rigid or articulated vehicles are most appropriate.

5. References

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