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Haptic Car-Following Support with Deceleration Control

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***Abstract*— A haptic gas pedal feedback system was developed at Delft University of Technology that translated the separation to a lead vehicle into continuous haptic cues (force, stiffness) on the gas pedal. During normal car-following situations, the haptic feedback cues were sufficient to reduce control activity and improve car-following performance. However, in more critical following situations drivers use the brake pedal to maintain separation with the lead vehicle. A deceleration control algorithm was designed that, in addition to the haptic feedback, provided increased deceleration upon release of the gas pedal during critical car-following situations. The deceleration control algorithm was tested in a fixed-base driving simulator experiment. Deceleration control improved car-following performance while reducing driver brake pedal control activity in the conditions tested.**

***Keywords*—car following, driver model, driver support system, haptic feedback, deceleration control algorithm**

I. Introduction

Driving is primarily a visual control task [1], [2]. It is therefore not surprising that a major cause of driving accidents is (visual) inattention of the driver [1]. This is the result of, for example, distraction by passengers, fatigue or in-vehicle devices, like mobile phones, navigation systems and in-vehicle audio systems. Especially car-following, it seems, is a task that frequently results in collision when attention is waning. For example, in the US, in 2005, 30.4% of all inter-vehicle crashes were rear-end collisions [3]. To warn drivers for impending hazardous situations, numerous warning and driver support systems are currently brought on the market or are under investigation.

Rear-end collision warning systems warn drivers for potential longitudinal collision dangers. Reference [4], for example, tested visual, auditory, and combined visual/auditory warning displays to investigate how driver headway maintenance behavior was influenced by these displays. They found that salient visual information resulted in increased following headways by as much as 0.5 s. Furthermore, they concluded that the auditory warnings tested were less effective in increasing driver headways than visual displays. Long term effects, however, were not investigated. Reference [5] did investigate long term effects. Their field tests of a visual time-headway (THW) display conducted over a period of 6 weeks showed that the time spent in short THW (<0.8 s) was reduced by approximately 25% and time spent in safer THW (>1.2 s) increased by approximately 20%. These results led them to conclude to "*...consider the installation of THW feedback devices on as many vehicles for as many drivers as possible.*"

Visual and auditory feedback systems that need to support drivers in collision avoidance situations present some inherent difficulties to both the designers and users of such systems. For visual systems, while apparently effective in increasing THW during normal driving conditions, it can be argued that, since these displays require visual attention in order to be useful, they suffer from the same human weaknesses that cause rear-end collisions in the first place. Auditory information is more suitable for warning signals, as it has great "attention grabbing" potential, but it usually requires higher levels of cognition to react appropriately compared to visual displays, hence valuable reaction time is lost [6]. Furthermore, auditory warnings need to be carefully balanced against false warnings and nuisance alerts to prevent human operators from ignoring the information provided [7].

Instead of using visual or auditory feedback, Delft University of Technology investigated a haptic gas pedal feedback system for car-following support. THW and time-to-contact (TTC) to a lead vehicle was transformed to haptic feedback which was communicated to the driver via the gas pedal [8], [9]. The design philosophy for this haptic feedback system was to give drivers continuous car-following information through tactile cues from the gas pedal [10]. Experimental results showed that, during a variety of car following conditions (0.5 s < THW < 2.0 s), haptic gas pedal feedback provided adequate support that reduced control activity of drivers, while slightly improving car-following performance at increased following THW [8], [11]–[13].

Reference [14] and [15] consider THW as safety indicators used to estimate the safety-margins of a traffic situation. TTC is characterized as a measure of criticality, or as a measure for the need to "…intervene by employing a suitable skill to avoid an impending crash" [15]. Reference [16] describe THW as "*...the time available to the driver of the following vehicle to reach the same level of deceleration as the lead vehicle in case it* *brakes.*" This time is independent of speed, hence, a faster braking response is needed when driving at smaller THW. Although the haptic gas pedal system increased following THW, as did other THW feedback devices tested by [4] and [5], there was no evidence that it also increased braking responses to decreasing THW (no evidence was presented for other THW feedback devices mentioned earlier either). More precisely, the haptic feedback system was mainly effective in case engine braking alone was sufficient for separation maintenance. Gas pedal control of velocity is inherently a-symmetric: one can accelerate much faster by depressing the gas pedal, than decelerate by releasing it. It was argued, therefore, that more functionality of the haptic feedback could be gained if deceleration responses to decreasing THW could be improved. This is especially true if one acknowledges that "*…selection of an appropriate headway distance is only one-half of the problem underlying the frequency of nose-to-tail crashes; initiation of braking response when required is of equal importance*" [20].

In line with the human-centered design philosophy that was adopted to develop the haptic gas pedal feedback system, it made sense to adopt a similar strategy to achieve the goal of amplifying the engine braking responses in concurrence with the haptic gas pedal feedback. This cybernetic approach is what [17] call response automation. In contrast to task automation [18], response automation is initiated by the system to "*...facilitate safer driving.*"

The idea of amplifying engine braking response, or deceleration control (DC), is not new and has been applied successfully before by [19], who conducted a field test with an instrumented vehicle. Their results indicate that the combined driver and controller input yields faster and stronger responses to lead vehicle decelerations. Overall, the support system reduced the frequency of close following and rapid closure situations due to increased vigilance of the driver to gap changes, while still following at a greater THW. Workload was not perceived to increase.

The combination of haptic feedback and DC effectively takes care of automation limitations, responsibility, dynamics, and efficiency. These four factors, according to [18], "*...influence how humans use automation design to support certain aspects of skilled human behaviour.*" By taking into account these principles, humans are therefore more likely to positively interact with the automation.

In our design, these principles were satisfied as follows. First, the limitations of the DC automation are confined to the same boundaries as the haptic feedback and are therefore identifiable via the detection of the haptic feedback from the gas pedal. Second, transfer of responsibility between automation and human is seamless, as the DC becomes active only when the driver is reducing the gas pedal depression, which effectively means the driver is already commanding the car to decelerate, the DC merely amplifies the command. Third, the strength of the deceleration that the DC algorithm can command is limited and is only active when the haptic feedback system is active and the driver is decreasing the gas pedal angle, making the system predictable. Fourth, by increasing the deceleration of the vehicle during close following when the gas pedal angle is decreased by the driver, the skilled execution of the car-following task is expected to become easier and more efficient, relieving the driver of some of the physical and mental burdens of that task.

To goal of this article is to describe the evaluation of our DC algorithm implementation. Verification of the effect of the DC system on car-following performance and control effort, in addition to the haptic feedback system was done in a fixed-base driving simulator experiment.

II. Deceleration Control Algorithm

Car-following can be characterized by cyclic behavior "*...around an approximate equilibrium spacing*" [21]. This cyclic equilibrium spacing can be conveniently described by time-headway (THW) and time-to-contact (TTC). Combining THW and TTC^{-1} yields the phase-plane graph typical of car-following, see Fig. 1.

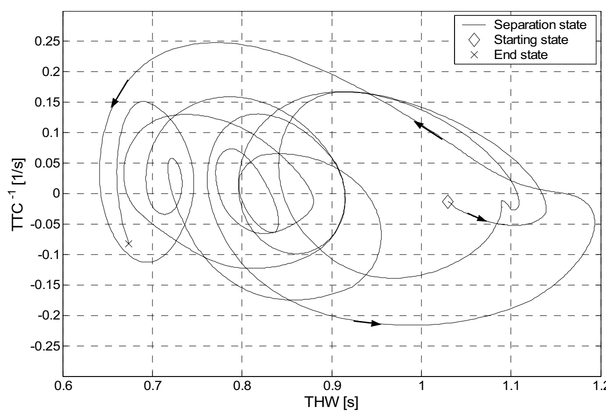


Fig. 1. An example of the typical cyclic behavior during car following.

Experimental data from an earlier driving experiment with a haptic gas pedal was used to develop the deceleration control algorithm [11]. Analysis of the driver gas-pedal release and brake-pedal depression points (those moments in the THW-TTC^{-1} phase-plane where drivers had reduced the gas pedal depression to 0% and increased the brake pedal depression from 0% respectively) yielded a formulation of an activation criterion for deceleration control. For reasons of system-authority limitations and driver comfort, the maximum deceleration that could be achieved by the system was set at 2.5 m/s^2.

The deceleration input to the vehicle, β_{DC}, generated by the DC algorithm was a function of the current THW and TTC and was expressed in a percentage of the maximum possible brake activation of the vehicle, see eq. (1). This deceleration was only generated when the driver decreased the gas-pedal angle α_p or when the gas-pedal angle $\alpha_p = 0\%$ (no gas pedal depression). A driver brake pedal input β_p would overrule the β_{DC} if $\beta_p > \beta_{DC}$. In other words, when the deceleration of the car commanded by the driver was larger than the deceleration generated by the DC, the DC deceleration was overruled (see Fig. 2). The maximum deceleration of 2.5 m/s^2 was achieved with 12.5% brake pedal depression.

$$0\% < \beta_{DC}(THW, TTC) < 12.5\% \tag{1}$$

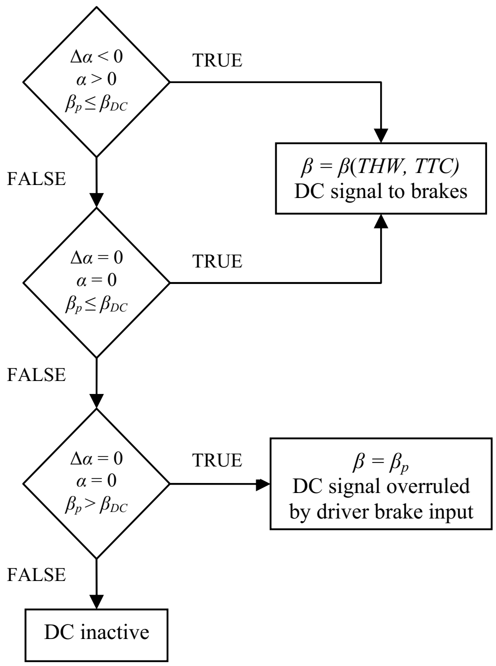


Fig. 2. Deceleration control algorithm logic. $\Delta\alpha$ is the time derivative of α, indicating gas-pedal movement direction. β_p is the driver brake-pedal input; β_{DC} is the DC algorithm brake input; and β is the real brake input to the vehicle.

III. METHOD

The purpose of the car-following experiment was to investigate the effect of the DC on driver car-following performance and control activity while drivers also received haptic feedback through the gas pedal. Driver car-following performance and control activity were defined as follows.

- Performance - the accuracy with which a desired target THW could be maintained;
- Control activity - the displayed activity of the driver to maintain the desired target

A. Experiment Design and Independent Variables

Two different system configurations were tested. One configuration was the configuration with haptic feedback alone (HF). This supports the driver with an increase of stiffness of the gas-pedal for decrease in THW [8]. The other configuration was the system with haptic feedback together with deceleration control (HF+DC). The order in which the HF and HF+DC conditions were driven by the subjects was balanced, that is, the first subject would drive the HF only condition first and then the HF+DC, the second would drive the HF+DC condition first and then the HF only, etc.

Two different values for time headway were considered (0.5 s and 1.0 s), and two different lead vehicle disturbance signals (HI and LO) with different frequency contents (bandwidth of 0.5 Hz and 0.3 Hz, respectively). In total, the subjects had to drive 8 different conditions (HF/HF+DC x THW0.5/THW1 x LO/HI), with each condition repeated three times. These conditions were presented in random order.

B. Apparatus

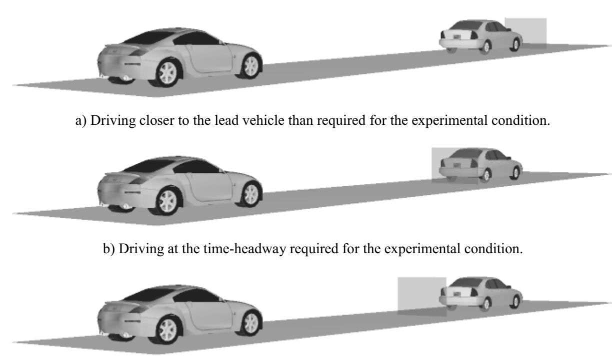
The driving experiment was performed using a fixed-base driving simulator. The driving scene was projected by a Sanyo PLC-XU33 multimedia projector, yielding a 3.3x2.1m visual with 60° horizontal and 40° vertical field of view. The simulation was updated at 100 Hz, the visual scene was rendered at 50 Hz. The actuated gas pedal was controlled with a dedicated control-loading computer running locally at 2000 Hz to allow for a smooth haptic sensation of realistic gas pedal dynamics. The actuator could deliver active force and stiffness feedback. An actuated steering wheel allowed drivers to steer their vehicle, and feel linearized break-out forces of the tires.

C. Subjects

Twenty subjects (9 female, 11 male) participated in the experiment. Mean age was 22.7 years with a SD of 1.7. Their mean driving frequency was 3.5 times per week (SD 1.7), driving on average 3760 km per year. All participants had valid drivers' licenses and were recruited from the general student population of Delft University of Technology. None were paid for their participation.

D. Experiment Task and Procedure

All subjects were asked to follow the lead car with a prescribed separation, i.e., the desired target time-headway THW_0. At the beginning of the experiment, the target time-headway was indicated by a red translucent rectangle, see Fig. 3.



a) Driving closer to the lead vehicle than required for the experimental condition.

b) Driving at the time-headway required for the experimental condition.

c) Driving further away from the lead vehicle than required for the experimental condition.

Fig. 3. Examples of the use of the THW-indicator in the driving simulator.

When the red translucent rectangle touched the rear-end of the lead vehicle, the driver was driving at exactly the required THW_0. The lead car was driving at a constant speed of 100 km/h. After a stationary car-following situation was established, the translucent rectangle disappeared and the lead car velocity was disturbed with a sum-of-sinusoids disturbance signal. During this period of lead car velocity disturbance, subjects had to maintain the separation at the time headway that was previously indicated by the translucent red rectangle, that is, the target THW_0. After approximately 80 seconds, the translucent rectangle appeared again, to allow subjects to correct for any drift from the desired THW_0. This correction in-between measurements was done to speed up the experiment and improve the quality of the data, since it ensured each measurement period started at an approximately similar separation state. Before performing the experiment for one of the two systems (HF or HF+DC), subjects had a training run of 5 minutes to get used to the system.

E. *Dependent Measures*

To determine the car-following performance and control effort, recorded data was used to derive the following performance and control activity measures

- Performance was represented by the mean and the standard deviations (SD) of the THW and inverse of time-to-contact iTTC.
- The control activity was represented by the standard deviation of the gas-pedal angle, α and the number of times drivers pressed the brakes (β).

F. *Hypotheses*

The increase in deceleration that was provided by the DC algorithm during close-following conditions was expected to improve the accuracy of the following task. It was expected that car following at small time headway separation was a more strenuous task than following at larger time-headways. The DC algorithm was therefore hypothesized to play a larger role in these cases.

1) HF+DC improves performance, especially in close following, i.e., with small THW.

The two disturbance conditions (HI and LO) were designed so that the level of power of the lead car velocity disturbance was equal. Performance was hypothesized to be equal for either velocity disturbance signal.

2) The two conditions for lead car velocity disturbance produce the same level of performance.

The addition of DC increased the deceleration potential of the own vehicle, especially under close following conditions. Releasing the gas pedal would, therefore, increase the following gap with the lead vehicle faster than without DC, and without requiring direct driver input on the brakes. It was expected that this would have significant effects in driver's control behavior.

3) The control activity during car-following with HF+DC active will be lower than HF.

Due to the faster gap-widening with DC, drivers would need fewer interventions with the brakes, leading to the final hypotheses.

4) HF+DC during car-following leads to less braking events by the drivers and drivers will spend less time braking their vehicle themselves.

IV. Results

A full-factorial Analysis of Variance (ANOVA) was conducted for the time domain data. The trends and significance of the results is discussed below in detail.

A. *Car-Following Performance*

Results indicate that the SD(THW) were significantly lower for the HF+DC system in all tested conditions, see Fig. 4. Especially in the low THW situations did the addition of DC bring about a relatively large reduction in the fluctuations in THW during following.

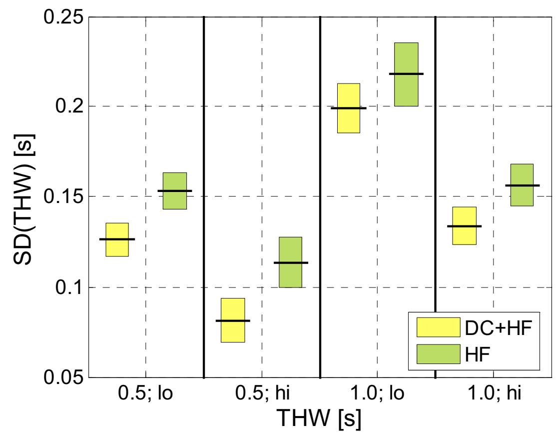


Fig. 4. SD of THW for all tested conditions. Horizontal lines represent mean values for all datasets. Bars represent 95% confidence levels, for different target THW and the different frequency (HI or LO) of lead vehicle perturbations.

From Fig. 5 it can also be seen that car-following performance for HF+DC also yielded less critical situations, since the minimum THW was significantly higher for all conditions, except during the high bandwidth disturbance at THW=1.0s.

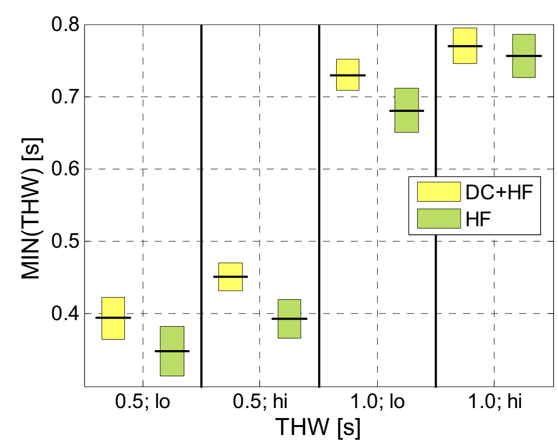


Fig. 5. Mean minimum THW for all conditions with 95% confidence levels, for different target THW and the different frequency (HI or LO) of lead vehicle perturbations.

The SD of the inverse of TTC, SD(iTTC), shows similar trends as the SD(THW), see Fig. 6. For HF+DC, the SD(iTTC) is significantly lower for almost all tested conditions. This is a clear indication of better following performance with fewer close following situations that potentially would have been unsafe.

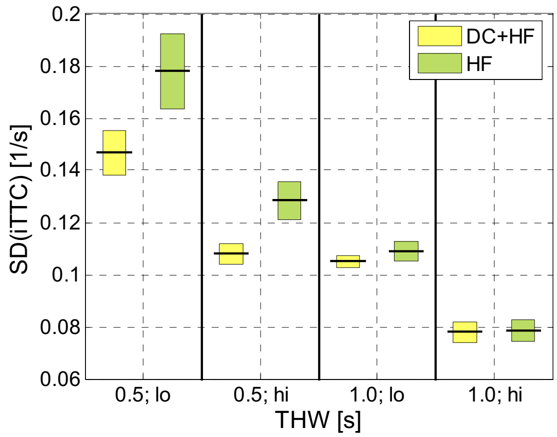


Fig. 6. Mean SD(iTTC) and 95% confidence levels, for different target THW and the different frequency (HI or LO) of lead vehicle perturbation.

B. *Control Activity*

Car-following performance was improved with HF+DC resulting in less unsafe situations and this could be achieved with the same kind of gas pedal control activity as for HF. Fig. 7 shows that the SD of the measured gas pedal depressions, α, was were not significantly different for the HF+DC and HF systems under all tested conditions.

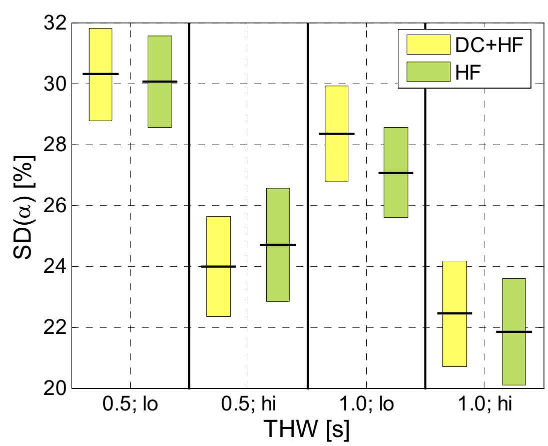


Fig. 7. Mean SD of the gas pedal depression, α, and 95% confidence levels, for different target THW and the different frequency (HI and LO) of lead vehicle perturbations.

When looking at the use of the brake pedal, it can be seen that when DC is used the number of braking events (β_{count}) is lower than for the HF system, especially for the high bandwidth disturbances, see Fig. 8.

Despite the increased deceleration response of the vehicle with DC, the maximum deceleration of the own vehicle is significantly lower when compared to HF in the THW=0.5 s conditions, as can be seen in Fig. 9. For the THW=1.0 s there are no significant differences. Thus, where the DC addition to HF is most useful, it increases following performance and safety conditions with less strong decelerations of the vehicle. This will also increase passenger comfort, as drivers will experience less severe decelerations due to the smoother and more controllable car-following activity.

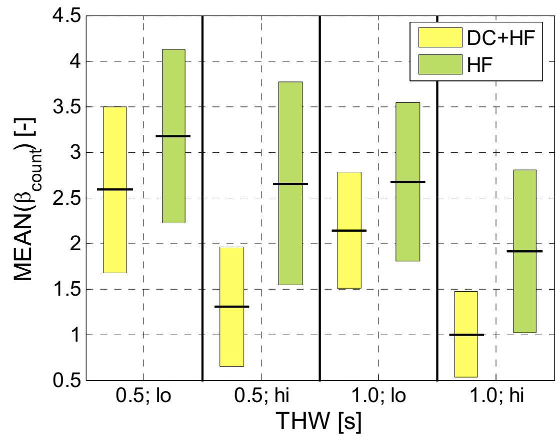


Fig. 8. Mean number of brake events during car following and 95% confidence levels, for different target THW and the different frequency (HI and LO) of lead vehicle perturbations.

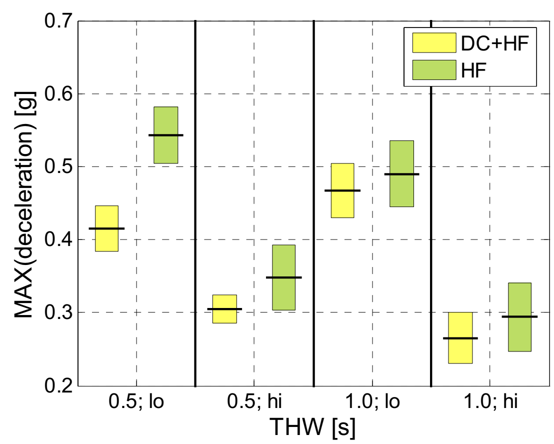


Fig. 9. Mean maximum decelerations and 95% confidence levels, for different target THW and the different frequency (HI and LO) of lead vehicle perturbations.

V. Discussion

As was expected, the designed deceleration control (DC) system increases car-following performance when used in combination with the previously designed haptic gas pedal. Because the own car is made more responsive to decelerations, it yields a smoother car-following behavior. This is reflected in the lower maximum measured decelerations.

The addition of DC did not decrease the gas pedal control activity of the drivers, contrary to what was hypothesized. It could be that the fixed-base driving simulator did not give drivers enough cues to notice the slightly faster deceleration behavior of the vehicle. Without the deceleration cues, drivers only had auditory and visual cues to determine their deceleration. Apparently these were not discriminatory enough to yield different gas pedal control behavior.

Nevertheless, the brake pedal needed to be used less when DC was active. Hence, driver brake pedal control activity was significantly lower when DC was active, mainly for the high bandwidth lead vehicle speed disturbances. The main benefit of DC is thus found in less need for drivers to use the brake pedal, while safety and comfort are increased.

These results are an improvement over the use of HF alone, which already yielded reduced gas pedal control activity when compared to a conventional gas pedal [8], [9].

VI. Conclusions

A deceleration control (DC) algorithm was designed and tested in a fixed base driving simulator, in situations where drivers already benefited from previously developed haptic feedback (HF) on the gas pedal. The DC algorithm increased the deceleration response of the own vehicle when the gas pedal was released during close car-following conditions.

HF+DC increased car-following performance while gas pedal control activity remained the same as for HF. Brake pedal control activity was reduced with HF+DC for high bandwidth lead vehicle speed disturbances.

The reduced brake pedal control activity for HF+DC resulted in reduced maximum measured decelerations of the own vehicle, increasing ride-comfort.

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