Car-following techniques: reconsidering the role of the human factor

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Abstract

Keeping correct distance between vehicles is a fundamental tenet in road traffic. New road signs and markings appearing on motorways aid drivers in determining this distance. However, the 'Nagoya experiment' (Sugiyama et al., 2008) revealed correct distance made following safe while also eventually destabilizing traffic flow. When traffic becomes dense, most drivers keep the minimum safety distance and brake when the vehicle ahead decelerates. The resultant chain reaction along the entire line of closely following vehicles causes for no apparent reason a traffic stoppage, known as a 'phantom' or 'shockwave' jam. The car-following models of Sugiyama et al. found certain speeds, traffic densities, and inter-vehicular distances combined to congest traffic. Drawing upon these and other phenomena (e.g., wave movement in Nature), car following by Driving to keep Inertia (DI) was conceived by us as an alternative to Driving to keep Distance (DD). Three studies explored possible prevention of 'phantom' jams by adopting DI. Using a driving simulator, affective and behavioural measures were taken (N=113). The results comparing the efficiency of DI vs. DD are summarized. DI promoted a more stable driver trajectory, in cognitive-affective and behavioural terms, and lowered fuel consumption by about 20%.

Background

This paper compares the efficiency of two elementary car-following (CF) techniques. Traffic flow efficiency may be judged by the prevalence of four driving modes: acceleration, deceleration, idling, and cruising (Tong et al., 2000). Efficient traffic cruises; congested traffic speeds up and slows down, polluting, wasting time and money, exasperating drivers, and risking life. As developed nations adopted stricter road safety standards, road salubrity worsened. Vehicle emissions now claim as many lives as crashes do, and possibly more (Caiazzo et al., 2013).

CF models were first developed in the early 1950s. Two main modelling efforts since then are the *Newtonian* or engineering CF models and the human factor

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models (Saifuzzaman & Zheng, 2014). The rationale behind engineering CF models is the possibility to appraise and formalise how drivers *naturally* follow each other. Characterising and parameterising Normative Driving Behaviour (NDB) have become important goals since the late 1990s (Brackstone & McDonald, 1999). Hence, human drivers' collective movement is observed in the context of how animals move in Nature, and then it is modellised and predicted. But rather than being a Nature issue, CF is *nurtured* by official criteria derived from such technical documents as the *Highway Capacity Manual* (TRB, 2010). Perhaps drivers practice certain NBD, but they also heed official advice: keep safety distance.

This advice stems from the engineering and human rationale shaping such historical programmes as the USA's Federal-Aid Highway Act of 1956 (Weingroff, 1996). During the 1920s to 1940s, soaring car ownership brought wealth and also fatalities and traffic jams. Authorities then had to base growth of an adequate motorway network on certain calculations. If 50,000 drivers go from city A to city B daily at a reasonable pace (say, 100 km/h), what road geometry and capacity (e.g., number of lanes) would be needed? The answer is straightforward: consider a standard car speed and braking time (taking gravitational force, and a standard friction coefficient). Then consider time needed to slow down from, e.g., the maximum official speed if a car ahead brakes suddenly. Traffic safely cruising through a given road section should result. The desired following distance, say, 2 seconds (s), is thereby set – shaped top-down. Drivers, however, normally flout limits. In England, 95.8% keep less than 2 s and 47.9% less than 1 s (Brackstone et al., 2002).

Talking about *road capacity* may be misleading. Topologically speaking, a bucket has a limited capacity and a hose (road) does not. What prevents roads from being functional is the way flows are *ordered*. Hence, congested roads express lack of road capacity beyond reason, but so pervasively that they have earned a metaphysical label: *phantom traffic jam* (Gazis & Herman, 1992). But, why should stoppages arise not due to a bottleneck (e.g., caused by lane loss)? To answer, a shift from modelling coupled vehicles is needed; now 'traffic flow is investigated as a dynamical phenomenon of a many-particle system' (Sugiyama et al., 2008; p. 2). The Nagoya experiment aimed to create an artificial traffic jam. Drivers followed each other in a circle whose perimeter was 230 m. Participants were instructed only: *follow the vehicle ahead in safety in addition to trying to maintain cruising velocity*. And so they drove and kept free flow. But when the number of drivers was increased to 22, fluctuations tripping backward easily broke the free flow. Eventually several vehicles had to stop for a moment to avert crashing.

At stake here is longitudinal mechanical waves (Cromer, 1981). *Keep safety distance* is good advice for coupling vehicles on a road section, but, when more than two cars follow, cars platoon into a nearly perfect medium for wave transmission. As shown by Sugiyama et al., at some point the oscillatory nature of flowing cars spread, backward, to form a soliton of 25 km/h. Cars platooned so nicely that drivers, by virtue of the instruction *follow the vehicle ahead in safety*, could not avoid propagating the corresponding disturbances. It did not matter if tight couplings and platoons came from external reduction of space (adding cars to the circuit) or from voluntary decision (leaving less than 1 s distance to the car ahead).

Considering wave mechanics, we either eliminate disturbances or deal with the medium transmitting them – the car-following platoon. The former are difficult to control, but not the latter. To cope with a lead oscillatory car (the shockwave origin), a following car must become shockwave proof. This remedy may be sought by reversing the goal of Sugiyama et al.: instead of observing the cause of congestion, seeking a means of prevention. To this end, two driving techniques (DD/DI) are compared to see if one is more effective, in cognitive-affective and behavioural terms, in promoting steadier travel. DD is Driving to keep Distance (from the lead car) and DI is Driving to keep Inertia (an adaptive, uniform speed) while car following. Proposing these two orthogonal driving techniques (aim for uniform distance vs. uniform speed) opposes the idea of NDB as a unique driving mode (Brackstone & McDonald, 1999) and assumes drivers can learn to follow a lead vehicle proactively by changing from an automatic to a controlled operative mode (Charlton & Starkey, 2011) and applying DD or DI as appropriate.

Overview of the studies

Goals

All three studies aimed to check if: A) the same driver could drive in DD and DI modes when following a lead 'disturbing' car; B) drivers could follow the driving techniques by heeding a 10 s instruction (three sentences); C) DD vs. DI differences in cognitive-affective and behavioural terms were significant (Blanch, 2015). The relevance of such emotions as anger, fear or anxiety in troubled CF contexts like congestion have been documented (Shinar & Compton, 2004; Zhang & Chan, 2014). Additionally, Study 3 (Ferruz, 2015) monitored the space occupied by eight virtual automaton DD drivers following either a DD or a DI participant.

Participants

All participants were licensed drivers (table 1). Some were students participating in exchange for academic credit; others were invited via billboards at nearby shops, driving schools, restaurants, and the like.

Table 1. Main demographics of participants

	Study 1 (Blanch, 2015)	*Study 2 (Blanch, 2015)*	*Study 3 (Ferruz, 2015)*
N	44	44	25
Gender	20 men/24 women	7 men/37 women	13 men/12 women
Age	23.3 years	20.7 years	21.3 years
Education	84.1% university	68.2% university	100% university
Driving experience	4.07 years	2.81 years	2.68 years
Km per year (%)	59.1% < 10,000	59.6% <10,000	44.0% <10,000

Design

The three studies shared the same experimental design, a repeated measures model controlling for order. Manipulation of driving technique (DD, DI) was the withinsubject factor. Order (DD-DI, DI-DD), randomly assigned, was the between-subjects factor. The set of dependent measures concerned cognitive-emotional and behavioural indicators (table 2). The participants' basic task consisted of advancing in a straight line, for 4 minutes on a simulated road, and following a vehicle accelerating and decelerating (until stopping) cyclically, similar to what occurs in very congested traffic.

Materials

The studies were conducted in two rooms at the faculty laboratories of a Spanish university: a booth where participants executed the tasks and an adjoining room with two-way glass and a monitor displaying the participants' psychophysiological responses. One main study objective was characterizing the psychophysiological activity under DD and DI. Skin conductance response (SCR) was recorded with an MP36 unit (BIOPAC Systems, Inc., Goleta, CA, USA) at a sampling rate of 50 Hz by using two disposable Ag-AgCl electrodes attached to the left hypothenar eminence. Mean SCR was calculated in microsiemens (μS) for all three experiments. The MP36 unit connected to a standard PC running Windows XP.

Self-report measures of affective state were also collected via the Self-Assessment Manikin (SAM), a nonverbal pictorial rating technique (Lang, 1980). SAM was applied to measure the affective state after task execution in the simulator. It provides data on three general affective dimensions: valence, arousal, and dominance. SAM has been widely used and validated in psychophysiological research and has normative data adapted to the Spanish population (Moltó et al., 1999). The valence scale ranges from 1 (pleasure) to 9 (displeasure). The arousal scale ranges from 1 (exciting) to 9 (relaxing). The control scale ranges from 1 (low dominance) to 9 (high dominance).

One of the earliest goals of this research was designing a 3D driving simulator able to run on a standard PC in distant workplaces and laboratories. *ReactFollower* (Impactware, 2014), based on UNITY software, was developed and customized to change certain parameters (e.g., speed, frequency of stop-and-go cycles, etc.) externally, via XML. The focus was on materialising the possibility to study DD/DI against different oscillatory patterns of the lead vehicle. Participants were shown three scenarios, always in one lane on a straight road: A) participant drives alone on the road (always in a natural position on the driver's virtual side of the vehicle); B) participant drives behind another vehicle travelling at constant speed of 3 m/s (10.8 km/h); C) participant drives behind another vehicle traveling with constant stop-and-go cycles of a sinusoidal function built at a mean speed of 3 m/s (data is presented only from C). Participants could control acceleration/deceleration of their vehicle only by pressing 'up/down' arrows on a computer keyboard. When 'up' was pressed, it accelerated and maintained a constant speed when released. When 'down' was pressed, it decelerated. Acceleration/deceleration was in discrete increments: to accelerate or decelerate continually participants had to press the keys repeatedly. The simplest option (keyboard) was preferred to enable all participants to use the software with basic hardware equipment, and to level differences in expertise with video game keyboards. Finally, no direction changes were intended, just regulating speed-distance in a straight lane. The driving simulator worked on an HP

TouchSmart iq522es computer with a 23-inch screen, NVIDIA GeForce 9300m GS video card and 4 GB RAM, Intel Core 2 Duo Processor T6400 2.00 GHz, and Windows 7 operating system. A precision Apple USB keyboard (PCB DirectIN V2012) was used. The simulator collected, among others, variables for speed, distance to leader, and fuel consumption (a gross estimate obtained considering variations in speed per frame, see table 2).

Procedure

Scenarios A/B were designed as controls. In scenario C, participants were asked to follow the lead vehicle and adopt one of two driving techniques (DD or DI) though they never received an explicit verbal label for either. The group performing the task in DD-DI order received this instruction first for DD: ‘In the simulated driving scenario that you will enter, you will see a vehicle ahead of you and it will not move at a constant speed. Sometimes it will go faster or slower. We ask you to travel behind that vehicle as closely as possible without risking a collision.’ Following this, they used the simulator and then were given the SAM scales. Afterwards, the instruction for DI was provided: ‘In the simulated driving scenario, you will see a vehicle ahead of you and it will not move at a constant speed. Sometimes it will go faster or slower. We ask you to travel smoothly behind the vehicle and maintain a constant speed, without letting the lead vehicle move too far away.’ Participants in the supplementary condition (DI-DD) read the same texts in reverse order.

Overview of main results

Data were subjected to a repeated measure ANOVA having two levels of driving orientation (DD, DI). Table 2 presents the main results concerning SCR, SAM scales (valence, arousal, dominance), and performance indicators (speed, distance, fuel consumption) from the three studies. Skin conductance was systematically and significantly higher for DD vs. DI in all three studies (S-1, $p < .001$; S-2, $p < .001$; S-3, $p = .046$, $\eta_p^2 = .16$ to .37). Regarding SAM subscales, differences concerning valence were significant only in Study 2, with DI being judged as more pleasurable than DD ($p < .001$, $\eta_p^2 = .58$). Arousal was significantly higher for DD vs. DI in all three studies (S-1, $p = .004$; S-2, $p < .001$; S-3, $p < .001$, $\eta_p^2 = .18$ to .49). Dominance was higher for DI in S-1 ($p < .001$, $\eta_p^2 = .27$) and S-2 ($p < .001$, $\eta_p^2 = .37$), but not in S-3 ($p = .11$). Regarding performance indicators: Average speed was lower for DI in all three studies (S-1, $p < .001$; S-2, $p < .001$; S-3, $p = .004$, $\eta_p^2 = .26$ to .35), and also speed variability (S-1, $p < .001$; S-2, $p < .001$; S-3, $p < .001$, $\eta_p^2 = .68$ to .85). Conversely, average distance to leader was always smaller under DD (S-1, $p < .001$; S-2, $p < .001$; S-3, $p < .001$, $\eta_p^2 = .57$ to .60). Finally, fuel expenditure was lower under DI in the three studies (S-1, $p < .001$; S-2, $p < .001$; S-3, $p < .001$, $\eta_p^2 = .75$ to .89).

Table 2. Means corresponding to main variables

	Study 1		*Study 2*		*Study 3*	
	DD	DI	DD	DI	DD	DI
Skin conductance	8.04	6.55	9.47	8.18	11.11	9.26
Valence	3.45	3.45	5.79	2.93	3.48	3.52
Arousal	3.93	5.07	3.11	5.61	4.24	5.76
Dominance	6.25	7.20	4.91	6.77	5.68	6.44
Speed (m/s)	3.08	3.05	3.07	3.03	3.07	3.03
Speed variability (m/s)	2.57	1.44	2.54	1.44	2.24	.99
Distance to leader (m)	6.60	11.90	7.70	17.60	9.25	19.40
Fuel expenditure (l)	19.4	15.0	18.6	15.1	19.7	13.9

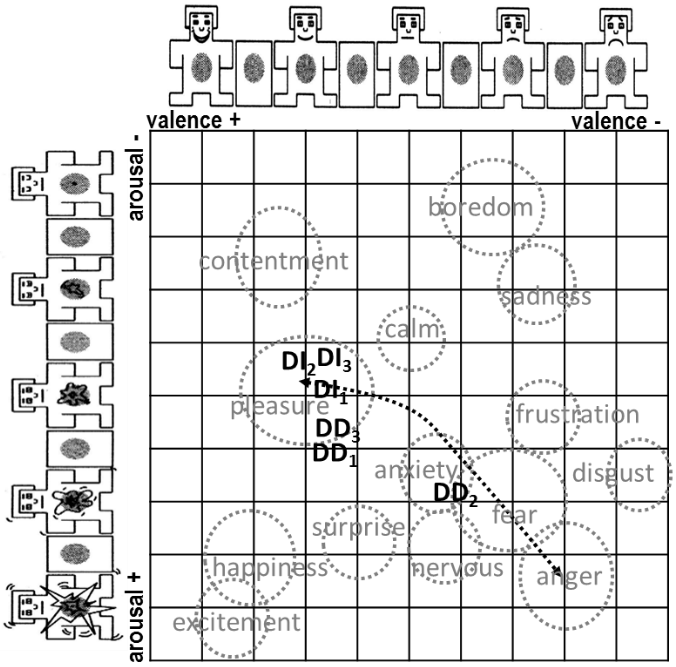

Figure 1. Mapping valence and arousal dimensions upon discrete emotions (Studies 1-3).

In sum, cognitive-affective indicators portrayed DI as a more comfortable way of following a lead oscillatory vehicle. SCR and SAM reports indicate DD drivers feel more arousal than DI ones (S1-3) and less dominance (S1-2), but only S2 shows valence differing. Following Cai & Lin (2011; see also Zhang & Chan, 2014), Fig. 1 tentatively maps results for valence-arousal dimensions (SAM) and discrete emotions. Performance indicators pointed to two orthogonal driving approaches, DD (aiming for uniform and shorter distance) vs. DI (aiming for uniform speed and longer distance). DI participants absorbed leader disturbance; moving at a more uniform speed, they were in turn easier to follow (table 2). DD drivers kept a more regular, shorter distance to the lead vehicle, thereby sacrificing speed stability. DI drivers kept speed more uniformly, but needed more distance to cushion the lead car's stop-and-go pattern.

Results concerning the platoon of eight virtual following drivers

Study 3 included new measures by the simulator: eight virtual DD cars followed each participant, who was unaware of it. The simulator registered the distances between eighth vehicle and lead vehicle, and between eighth vehicle and participant. Average distance between eighth vehicle and lead vehicle was similar for each condition (DD: M = 117.3 m; DI: M = 118.95 m; p = n.s.). However, the distance between participant and leader was longer under DI (table 2), this fact obscuring the actual space required by the platoon. But differences between the eighth vehicle and the participant (DD: M = 108.03 m; DI: M = 99.55) were significant ($p < .001$; $\eta_p^2 = .84$). As measures of speed variability suggest (table 2), DI furnished platoon stability, and therefore optimised space on the road.

Discussion

DI drivers feel more comfortable, drive more steadily, and are easier to follow (even for DD virtual drivers). First, similar to differences found between car and truck drivers, the latter normally holding speeds more constant than the former (Ossen & Hoogendoorn, 2011), drivers in these three studies can drive under DD vs. DI mode when following a lead 'disturbing' car. Second, drivers can follow the driving techniques by heeding a 10 s instruction (three sentences) or a short video. Third, DI promotes a more stable driver trajectory than DD does, in cognitive-affective and behavioural terms. Fourth, all studies showed significant differences, always the same type, in these terms dependent upon whether participants applied DD or DI.

Potential relevance of training to learning DD/DI

Participants in the three studies received the same main instructions about the driving techniques. But compared with Studies 1 and 3 (short sentences described in *Procedure*), the set of instructions in Study 2 explained how to drive DD or DI with one of two videos (each 4 minutes approx.). Each video presented an explanation of congestion by one of two fictitious traffic institutes (named by acronyms, I.T.F.; C.M.D.). Both videos shared the same explanation for congestion (how congestion emerges), and then advised one of two behavioural alternatives (DD or DI). The main recommendation on how to drive was embedded (written) at the videos' end. Also, instruction for Studies 1 and 3 was direct, even more so than for Study 2 (Blanch, 2015). The difference in valence (SAM) in Study 1 and 3 vs. Study 2 is likely due to perceived authority of an agency (I.T.F.) recommending DD, the more stressful and harder to manage alternative (resulting also in higher arousal and lower dominance).

Limitations of the studies

This set of exploratory studies of DD/DI techniques contains some limitations. Compared with the average national driving population, study participants were more educated, younger, and unlikely to have driving habits ingrained by many years behind the wheel. Most were ‘low mileage’ drivers. They may have learned faster and been more amenable to new techniques than the average driver would be. Also, future studies should improve the ecological validity of *ReactFollower* (e.g., by using accelerator and brake pedals).

The main challenge, however, concerns comprehending how drivers’ emotions, CF and congestion are linked. CF epitomizes the two elementary driving goals: safe/arrive. Inadequate distance concerns safety while slow speeds delay arrival. The literature shows anger is likely when drivers’ goals are blocked by other drivers, and anxiety/fear emerge when drivers face probable danger (Mesken et al., 2007; Roidl et al., 2013; Zhang & Chan, 2014). Emotions, acting as a feedback loop concerning course of action, reset priorities and actions (Carver & Scheier, 2012). Congested CF increases opportunities for anger/aggression (tailgating, blocking of lane change for reaching exit), anxiety/fear (near rear-end crash) and relief (crash avoidance). This mix of emotions – Fig. 1’s dotted line – may well cause oscillations in speeds and flow density. The data presented revealed differences in CF when either DD or DI was prompted, with an impact on arousal, but mobility goals – a key element concerning valence – were not manipulated. Future studies should analyse how emergence of certain emotions during DD/DI impact CF and congestion.

Concluding remarks

This paper aims to connect research on current car-following trends (Sugiyama et al., 2008) with operationalisation of two alternative driving techniques. For different reasons, drivers couple in dense traffic when lead vehicles are dictating the pace and keep a close, constant distance to each other. Learning a complementary way for adapting speed to oscillatory patterns of lead cars can contribute to alleviating congestion and its attendant ills while also stabilising successive car platoons.

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References

Blanch, M.T. (2015). *El seguimiento de un vehículo en el desplazamiento en línea: caracterización psicofisiológica y conductual de dos formas básicas de conducción*. PhD thesis. University of Valencia, Spain.

Brackstone, M. & McDonald, M. (1999). Car-following: a historical review. *Transportation Research Part F*, *2*, 181-196.

Brackstone, M., Sultan, B., & McDonald, M. (2002). Motorway driver behaviour: studies on car following. *Transportation Research Part F*, *5*, 31-46.

Carver, C.S. & Scheier, M.F. (2012). Cybernetic Control Processes and the Self-Regulation of Behavior. In R.M. Ryan (Ed.), *The Oxford Handbook of Human Motivation* (pp. 28-42). New York: Oxford University Press.

Cai, H. & Lin, Y. (2011). Modeling of operators' emotion and task performance in a virtual driving environment. *International Journal of Human-Computer Studies*, *69*, 571-586.

Caiazzo, F., Ashok, A., Waitz, I.A., Yim, S.H.L., & Barrett, S.R.H. (2013). Air pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005. *Atmospheric Environment*, *79*, 198-208.

Charlton, S.G. & Starkey, N.J. (2011). Driving without awareness: The effects of practice and automaticity on attention and driving. *Transportation Research Part F*, *14*, 456–471.

Cromer, A.H. (1981). *Física para las ciencias de la vida*. Barcelona: Editorial Reverté.

Ferruz, A.M. (2015). *Análisis de la intervención del factor humano en el movimiento vehicular en línea a partir de dos modelos de conducción*. Final Degree Thesis. University of Zaragoza, Spain.

Gazis, D.C. & Herman, R. (1992). The Moving and 'Phantom' Bottlenecks. *Transportation Science*, *26*, 223-229.

Lang, P.J. (1980). Behavioral treatment and bio-behavioural assessment: computer applications. In J.B. Sidowski, J.H. Johnson, and T.A. Williams (Eds.), *Technology in Mental Health Care Deliver Systems* (pp. 119-137). Norwood, NJ: Ablex.

Mesken, J., Hagenzieker, M.P., Rothengatter, T., & de Waard, D. (2007). Frequency, determinants, and consequences of different drivers' emotions: An on-the-road study using self-reports, (observed) behaviour, and physiology. *Transportation Research Part F*, *10*, 458-475.

Moltó, J., Montañés, S., Poy, R., Segarra, P., Pastor, M.C., Tormo, M.P., Ramírez, I., Hernández, M.A., Sánchez, M., Fernández, M.C., & Vila, J. (1999). Un nuevo método para el estudio experimental de las emociones: El International Affective Picture System (IAPS). Adaptación española. *Revista de Psicología General y Aplicada*, *52*, 55-87.

Ossen, S. & Hoogendoorn, S. (2011). Heterogeneity In Car-Following Behavior: Theory And Empirics. *Transportation Research Part C*, *19*, 182-195.

Roidl, E., Frehse, B., Oehl, M., & Höger, R. (2013). The emotional spectrum in traffic situations: Results of two online-studies. *Transportation Research Part F*, *18*, 168-188.

Saifuzzaman, M. & Zheng, Z. (2014). Incorporating human-factors in car-following models: A review of recent developments and research needs. *Transportation Research Part F*, *48*, 379-403.

Shinar, D. & Compton, R. (2004). Aggressive driving: an observational study of driver, vehicle, and situational variables. *Accident Analysis & Prevention*, *36*, 429-437.

Sugiyama, Y., Fukui, M., Kikuchi, M., Hasebe, K., Nakayama, A., Nishinari, K., Tadaki, S., & Yukawa, S. (2008). Traffic jams without bottlenecks –

experimental evidence for the physical mechanism of the formation of a jam. *New Journal of Physics*, *10*, 3001-3007.
Tong, H.Y., Hung, W.T., & Cheung, C.S. (2000). On-Road Motor Vehicle Emissions and Fuel Consumption in Urban Driving Conditions. *Journal of the Air & Waste Management Association*, *50*, 543-554.
Transportation Research Board [TRB] (2010). *Highway Capacity Manual*. 5th Ed. National Research Council (USA). Washington, DC.
Weingroff, R.F. (1996). Federal-Aid Highway Act of 1956: Creating the Interstate System. *Public Roads*, *60*(1). Retrieved 25 January 2015: http://www.fhwa.dot.gov/publications/publicroads/96summer/p96su10.cfm
Zhang, T. & Chan, A.H.S. (2014). How appraisals shape driver emotions: A study from discrete and dimensional emotion perspectives. *Transportation Research Part F*, *27*, 112-123.