

## Invited reply



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# Invited reply: Reply to Blocken's comment by the authors (2025) Marro *et al.*

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## 1. Introduction

New drafting configurations optimizing pacer formation around a designated elite runner have been identified based on wind tunnel experiments in a recent study [1]. This work was motivated by two recent attempts to complete the 42.195 km distance in less than 2 h: Nike Breaking2 and INEOS 1:59 Challenge, hereafter referred to as NB2 and INEOS, respectively. NB2 took place at the Monza racetrack in 2017, involving three top runners, L. Desisa, E. Kipchoge and Z. Tadese. E. Kipchoge managed to finish the race in 2:00:25. INEOS took place in Vienna in 2019, where E. Kipchoge achieved the incredible feat of running the distance in 1:59:40. The success of INEOS may be attributed to differences between the two events: Kipchoge's superior fitness, favourable weather conditions, advanced footwear, the crowd's support and also the route selection [2]. A major difference between the two events, however, was the improved configuration of pacers positioned around the designated runner [3,4]. Pacer formations ensure reduced drag, and therefore lower oxygen consumption and improved efficiency for the elite runner [3]. A configuration of 6 diamond-shaped pacers was used for NB2, while for INEOS, 7 pacers were employed, with 5 positioned in a V-shape in front of Kipchoge and 2 positioned behind him. A total of 30 runners for Nike and 41 for INEOS took turns during the race.

Marro *et al.* [1] provided empirical findings from 1/10th scale wind tunnel experiments for marathon runners in various formations and reported the precision and validation of their apparatus. These findings support the report that the INEOS formation provided substantial drag force reductions, though our findings differ in magnitude from those previously reported. A new, more efficient formation was also identified in [1], again with 7 pacers and other formations may prove even better. There is clearly a need for more well-documented experimental and CFD studies on the aerodynamics of runners. In what follows, we respond to the issues raised by Blocken [5].

## 2. Selected experimental set-up

### (a) Manikin

A first criticism concerns the geometry of the manikin, which would not be sufficiently realistic compared to a real runner. The choice of the manikin was motivated by the possibility of having movable joints to evaluate the influence of different positions on drag force; the reader can refer to Section 3.a in [1], given the complex bio-mechanics of running [6]. The legs flex and extend at the knee and ankle during the support phase, the arms oscillate, counter-rotation of thorax and arms counteract the torque generated by leg acceleration during the aerial phase. This analysis was not performed before and shows that drag force is minimally influenced by the position of the manikin with a relative drag variation less than 3%. This result could also justify the unrealistic posture depicted in Blocken's figure 1 [5] where the manikin runners have both feet on the ground simultaneously, which does not occur in running gaits.

Another limitation shared by both studies is that identical copies are used in pacer formations. The NB2 and INEOS marathons utilized 30 and 41 different pacers, respectively, and the anthropometric dimensions of those runners varied a great deal. As an illustration, the athletes ranged from 1.87 metres tall and 75 kg for F. Ingebrigtsen to a minimum of 1.60 metres tall and 54 kg for Z. Tadese and 1.67 metres tall and 52 kg for H. Bor. The need for a model perfectly identical to a particular real-life runner therefore seems unnecessary, given such diversity.

Despite its appearance, which is of course not evocative of an elite runner, the manikin used in [1] is characterized by a realistic anthropometric profile. Indeed, the ratio between the chest girth with respect to the thigh girth is 1.84 for the manikin and  $1.81 \pm 13\%$  for a long-distance runner [7,8]. The ratio between the chest girth and waist girth is equal to 1.4, whereas for a long-distance runner, the mean value is approximately  $1.26 \pm 10\%$ .

The simplified geometry of the manikin is undoubtedly a limitation of the study, but its impact is hard to quantify. Nevertheless, it does not seem to be the dominant factor compared to other simplifications, as induced by static manikins having identical shapes, which are assumptions adopted in almost all similar studies.

### (b) Wind tunnel testing

In the comments by Blocken [5], two key issues are raised with the Reynolds number value and the blockage ratio. The Reynolds number is approximately half that of a full-scale marathoner. This point is addressed in [1], where it is shown that the drag coefficient follows a plateau for this range of Reynolds number values. This approach is often used in aerodynamic studies with identical flow regimes, including Blocken *et al.* [9]. The experiments were performed at a Reynolds number value around 1/4 of the full-scale value.

To the best of the authors' knowledge, the effect of Reynolds number  $Re$  on running has not been thoroughly investigated. Pugh [10] observed only minor variations in  $C_D$  within the range  $4.0 \times 10^5 < Re < 1.5 \times 10^6$  for both running and walking. Pecchiari *et al.* [11] reported that  $C_D$  remains independent of  $Re$  for full-scale walking subjects, though some dependence was noted

for runners at lower speeds (around  $10 \text{ km h}^{-1}$ ). It should be noted that these differences between running and walking do not apply to static models.

Other published data consider different sports and present varying conclusions. For example, in alpine skiing, Reynolds number effects persist up to full-scale speeds of  $25 \text{ m s}^{-1}$  ( $90 \text{ km h}^{-1}$ ), while in ice skating, these effects are noticeable up to  $12 \text{ m s}^{-1}$  ( $43 \text{ km h}^{-1}$ ). In cycling, the impact of Reynolds number varies significantly depending on the rider's position. Its effect is significant when the cyclist assumes the pursuit position [12], but it is negligible in the dropped position [9]. A runner is not a perfectly aerodynamic body compared to a skier or skater, who adopt specific positions and wear optimized clothing and helmets, with higher flow velocities. The lack of data, however, highlights the need for further studies to assess the potential impact of Reynolds number in running.

Second, all drag coefficient values provided in [1] are raw data, without any correction applied to take into account blockage effect. To allow comparisons with future numerical simulation results, it is usually recommended to take into account the test section in the computational domain to correctly include these somewhat controversial installation effects [13]. For a closed wind tunnel, the measured drag coefficient is expected to slightly increase due to blockage effects. For the solo runner [1], the solid blockage ratio is  $\sigma_s = 2.6\%$  where  $\sigma_s$  is the manikin frontal area  $A$  to test-section cross-sectional area, whereas  $\sigma_s \leq 7.8\%$  for the INEOS formation and  $\sigma_s \leq 5.2\%$  for the swordfish-like formation. However, the load cell is mounted on the designated runner, which presents a solid blockage closer to the those of a solo runner. Using Maskell's correction [13], the relative drag correction is about 2% for the solo runner, and the relative error between the two drafting formations, swordfish and INEOS, is about 1%. Table 3 in our study [1] remains thus quite relevant to discriminate configurations.

Finally, the drag force of a finite-length cylinder has also been measured [1] to validate the experimental protocol, for which  $\sigma_s = 6.6\%$ , with  $C_D \simeq 0.95$  yielding a corrected drag coefficient  $C_D \simeq 0.92$ , in agreement with the value provided by expression (3.1) of the study.

### 3. Analysis of drag reduction

The analysis of drag reduction induced by various pacer configurations first requires a reliable estimate of the drag force acting on the designated runner. Blocken [5] provides two values of the drag force for a solo runner, 6.86 N and 6.25 N, obtained numerically and experimentally, respectively. No specific details are provided regarding the methodologies or data used to compute these values, making it difficult to verify their accuracy. By arbitrarily taking the CFD solution as a reference, the experimental drag force provided by Blocken [5] underestimates this value by 10% whereas our measurements (7.68 N) overestimate it by 11%, see table 4 in [1]. These differences indicate that, for a solo runner, the drag coefficient reported in [1] aligns with values presented in previous studies [14–16].

Despite the reliability observed for the drag coefficient of a solo runner, any minor error caused by the simplified shape of the manikin could be propagated and amplified throughout more complex formations. This effect has not been extensively investigated in the literature, so we can not confirm or rule it out.

Blocken *et al.* [17] noted that in cycling pelotons, the agreement between numerical and experimental results worsened as the number of riders increased or the configurations became more complex. They attributed the discrepancies to the effects of some physical elements present in the wind tunnel, vibrations of the cyclist models, features of the shear layer and finally very minor misalignments of the rider model. We lean towards this latter explanation. A large scattering can actually be observed in the literature, even for simple configurations. For a single pacer (formation 2), Schickhofer & Hanson [18] found a drag force reduction of  $-70\%$ , whereas Fernandes & Maldonado [4] reported  $-52\%$ . These discrepancies may largely be attributed to the high sensitivity of the drag force to the position of the leading pacer, although other factors related to the model's geometry or experimental set-up may also play a role. In particular, a variation of

10% in the separation distance leads to differences in the experienced drag force ranging from 10% to 20%, as shown in figure 9 and 11 in [1] and also in figure 6 of Schickhofer & Hanson [18]. By accurately setting the pacer position, our data are found to be in better agreement with the recent results by Fernandes & Maldonado [4]. A difference of 7% for a single leading pacer and of 5% for two parallel leading pacers (formation 4) are found.

## 4. Time savings

The time savings of the different pacer formations were estimated by considering the variation in the running economy, representing the rate of oxygen uptake for running at a specified velocity, due to a reduction of the drag force acting on the marathoner. This method is customary and has the distinct advantage of being independent of specific tracks [3,18], enabling direct comparison between different configurations (INEOS versus NB2 in this case).

## 5. Concluding remarks

In this comment, we have addressed the criticisms raised in [5] with respect to our experimental study on drag reduction induced by drafting formations in elite marathon runners [1]. The limitations of our study have been examined, including the simplified model geometry, the use of static (non-running) mannequins, the blockage ratio and Reynolds number similarity.

This discussion points out two aspects that deserve careful consideration and further investigation. The first is the need to evaluate the impact of the Reynolds number on running aerodynamics. Second, the complex movements of a runner, mainly due to the oscillation of arms and legs, raise questions as to the definition of an appropriate equivalent geometry for the model. Almost all studies in the scientific literature, both experimental and numerical, are based on static models, which introduce a simplification in drag force estimates that could be significant. Further research is needed to answer these questions.

Finally, the agreement between our results [1] and well-documented data from previous studies is underlined, particularly for a solo runner and simple pacer formations. While we cannot entirely rule out that the discrepancies observed in more complex configurations may be due to the simplified shape of the mannequins used in our study, it is believed that minor misalignments among the runners provide a more compelling explanation. We hope it will contribute to advancements in optimizing drafting formations and inspire future breakthroughs in marathon performance.

**Data accessibility.** This article has no additional data.

**Declaration of AI use.** We have not used AI-assisted technologies in creating this article.

**Authors' contributions.** M.M.: conceptualization, data curation, formal analysis, investigation, methodology, validation, writing—original draft and writing—review and editing; C.B.: conceptualization, formal analysis, funding acquisition, investigation, methodology, writing—original draft and writing—review and editing; P.S.: conceptualization, formal analysis, funding acquisition, investigation, methodology, writing—original draft and writing—review and editing. All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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