Modeling wind and altitude effects in the 200 m sprint

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Abstract: A quasi-realistic mathematical model of 100 m sprint performances is modified to simulate the 200 m race, a portion of which is run around a curve. The calculated effects of wind are complex functions of the wind direction and the lane in which the athlete is running. It is shown that wind and altitude-assisted marks for the 200 m are in some cases significantly higher than the corresponding adjustments for the 100 m sprint under similar conditions. The estimated advantage of a 2 $\mathrm{m\,s^{-1}}$ tail wind is between 0.09–0.14 s, with the greater advantage going to the runner in the outside lane. At higher altitudes (>2000 m), these corrections can rise to over 0.3 s. Crosswinds can further enhance the performance by over 0.5 s due to decreased drag forces around the curve. A consequence of these results suggests that record ratification procedures for such performances be reconsidered. The model is also used to study Michael Johnson's world record race of 19.32 s from the 1996 Olympic Games in Atlanta, Georgia.

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Résumé : Nous utilisons un modèle mathématique semi-réaliste des performances d'une course de sprint sur 100 m afin d'étudier les performances d'une course de 200 m, une portion de laquelle suit une courbe. Les corrections calculées pour le vent sont des fonctions compliquées de la direction du vent et du couloir dans lequel l'athlète court. Nous trouvons que l'avantage dû au vent et à l'altitude pour le 200 m est dans certains cas significativement plus important que pour le sprint de 100 m dans les mêmes conditions. L'avantage estimé sous un vent arrière de 2 $\mathrm{m\,s^{-1}}$ est entre 0,09 et 0,14 s, la correction maximale allant au couloir extérieur. À plus haute altitude (>2000 m), ces corrections peuvent atteindre 0,3 s. Le vent de côté peut améliorer encore plus la performance par 0,5 s, à cause de la diminution de la force de résistance dans la courbe. Une conséquence de ces résultats suggère que les procédures de ratification de ces performances doit être revue. Nous utilisons aussi ce modèle pour étudier le record du monde de 19,32 s de Michael Johnson lors des Jeux Olympiques d'Atlanta en 1996.

[Traduit par la Rédaction]

1. Introduction

The quasi-physical model presented in ref. 1 provides a realistic simulation of 100 m races, including accurate matching of recorded 10 m split times and velocity profiles. By incorporating a term accounting for the modification of drag effects, the effects of wind and altitude may be studied. Many authors have

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studied wind and altitude corrections in the 100 m [1–9], and it is generally agreed that a 2.0 m/s tail wind provides about a $+0.10$ s advantage.

There have been fewer studies that address wind and altitude effects in the 200 m sprint. This is in part due to the fact that unlike its shorter counterpart, the first half of the 200 m race is run around a curve, and the wind effects are not as easily accounted for during this portion. Other authors [10–14] have addressed issues regarding performance discrepancies due to track curvature and drag effects, and several of their results concerning the 200 m will be discussed at length in Sect. 6.

By the nature of the model discussed in ref. 1, though, it is relatively straightforward to study sprint races run for any duration. Thus, with a minor modification to account for energy loss on the curve, this article will examine the effects on performances for winds blowing in arbitrary directions at the time of the race.

2. The quasi-physical model

The model presented in ref. 1 is based on a system of coupled differential equations

$$\begin{aligned}\dot{d}(t) &= v(t)\\ \dot{v}(t) &= f_{\mathrm{s}} + f_{\mathrm{m}} - f_{\mathrm{v}} - f_{\mathrm{d}}\end{aligned} \tag{1}$$

where $d(t)$ is the distance traveled by the athlete in a time t. For the acceleration term, f_{s} is called the drive term, f_{m} the maintenance term, f_{v} the velocity term, and f_{d} the drag term. These are explicitly functions of t, $v(t)$ and the wind speed w

$$\begin{aligned}f_{\mathrm{s}} &= f_0 \exp(-\sigma\, t^2)\\ f_{\mathrm{m}} &= f_1 \exp(-c\, t)\\ f_{\mathrm{v}} &= \alpha\, v(t)\\ f_{\mathrm{d}} &= \frac{1}{2}\left(1 - 1/4 \exp\{-\sigma t^2\}\right) \rho A_{\mathrm{d}}\, (v(t) - w)^2\end{aligned} \tag{2}$$

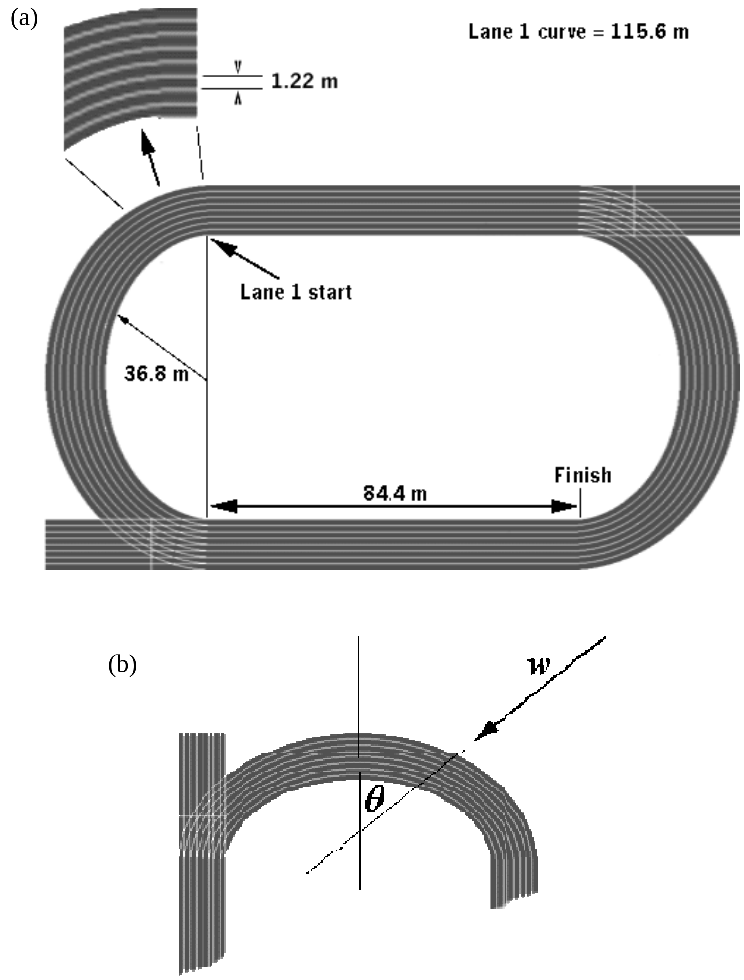
A quantity of crucial importance in the above equations is the "modified drag area" $A_{\mathrm{d}} = C_{\mathrm{d}} A/M$, where A is the athlete's cross-sectional area (in m^2), C_{d} the drag coefficient, and M the mass (in kg). It is this term that determines the effects of wind and altitude on the sprint race. For typical values of M and A ranging between 75–80 kg and 0.40–0.50 m^2, respectively, coupled with a drag coefficient estimate of about 0.5, a reasonable value of $A_{\mathrm{d}} = 0.00288\ \mathrm{m}^2\ \mathrm{kg}^{-1}$ produces the desired wind/altitude corrections. The reader is referred to ref. 1 for a full explanation of these terms and the associated rationale behind each.

3. The 200 m race

Figure 1 shows the dimensions and configuration of a standard IAAF track, and the following features should be noted [15].

- The track comprises 8 lanes, with an overall length of 400 m in lane 1 (the inside lane). It consists of two straight portions 84.39 m in length, and two semi-circular curves of approximate length 115.61 m. The radius of curvature for lane 1 is 36.8 m.
- Each lane is 1.22 m in width, with a 5 cm line separating each.
- The 200 m start line in lane 1 is at the beginning of the curve, such that the race is composed of 115.61 m curve $+84.39$ m straight. The starting line for each subsequent lane is staggered by 3.83 m to make this configuration consistent for all lanes.

Fig. 1. (*a*) Standard IAAF track configuration. (*b*) Arbitrary crosswind w blowing at angle θ.



3.1. Modification for curvature

To account for the curve, the following two modifications are made to (1). First, a damping term is applied to the the propulsive forces in (1), such that

$$\dot{v}(t) = \beta(f_\mathrm{s} + f_\mathrm{m}) - f_\mathrm{v} - f_\mathrm{d} \tag{3}$$

where

$$\beta(v(t); R_l) = \left(1 - \frac{\xi v(t)^2}{R_l}\right) \tag{4}$$

with $\xi > 0$ a scaling factor that can be used to fit the model split (i.e., 10 m interval) times to those recorded in actual races. The general form of (4) is chosen to include a dependence on the velocity $v(t)$ of the sprinter, as well as the radius of curvature R_l of lane l. In compliance with the track configuration discussed in Sect. 3, R_l is defined as

$$R_l = 36.80 + 1.22(l - 1) \tag{5}$$

and so the total length of the curve for lane l is $d_l = \pi R_l$. Note that when $\xi = 0$, or in the limit $R \to \infty$, $\beta \to 1$ the original form of the model is recovered. This damping term differs slightly from that proposed in ref. 10, which involved the vector sum of forward and centrifugal forces (although ultimately, it can be argued that the form presented herein is a linearized version of the cited term). The damping parameter is added to account for the fact that the sprinter does not feel the full radial acceleration generated by his angular velocity due to running posture and style.

3.2. Wind assistance on the curve

The main barrier to simple wind-assistance calculations in the 200 m is the variability of conditions around the curve. Since the sprinter's frontal cross-sectional area is rotating, a wind blowing in a fixed direction will have different effects depending on the athlete's position on the bend.

Before proceeding, the following main assumptions of this study should be highlighted. All wind speeds are assumed to be *constant* in both magnitude and direction for the duration of the race, and also across the stadium or race venue. In reality, neither assumption is perhaps terribly accurate (see, for example, refs. 16, 17, and 18). Most recently, Linthorne [18] has suggested that the wind gauge reading can only be accurate to within $\pm 0.9 \text{ m s}^{-1}$!

To establish a working coordinate system, we define θ to be the angle from which the wind direction deviates from the 100 m straight. Furthermore, we define ϕ as the angular distance around the curve traveled by the sprinter. Due to the staggered start, the value of $\phi(t)$ will depend on the lane assignment, so for lane l, the initial value is

$$\phi_0 = -\frac{\pi}{2} + \frac{(d_l - 115.6)}{R_l} \tag{6}$$

So, one can estimate the component of the wind in the forward direction of the athlete at time t as

$$w_c(t) = w \sin(\phi(t) - \theta) \tag{7}$$

Note that for a wind completely down the straight ($\theta = 0$), at the midpoint or "top" of the curve ($\phi(t) = 0$), the value of $w_c(t)$ vanishes, since at that moment the wind is entirely a crosswind. Similarly, a tail wind ($w > 0$) will be felt as a head wind (and vice versa) in the initial stages of the race, when $\phi(t) < \theta$. Crosswinds are again assumed to be negligible (a condition that may begin to break down for excessively strong winds, to be discussed further).

4. General results

As in ref. 1, the equations of motion (1) are numerically integrated using a fourth-order Runge–Kutta–Fehlberg algorithm. The integration is divided into two phases, with the final conditions ($d(t)$, $v(t)$, etc. …) of the curved portion of the race being the initial conditions for the linear portion of the race. The magnitude of the corrections will ultimately depend on the value of θ with which the wind intersects the straight. This component of the wind speed is also that which is recorded by the wind gauge, assuming a wind is blowing uniformly across the stadium.

Due in part to a general lack of split data for the 200 m sprint, the parameter selection is somewhat looser than for the 100 m [1]. The data that are available (see, for example, ref. 19) suggest that the average splits for a sub-20 s 200 m race are around 5.75–5.80 s (50 m), 10.20–10.25 s (100 m), and 14.90–15.00 s (150 m). The exact splits depend on numerous factors, including lane assignment (tighter curves will produce slower 50 m and 100 m splits), wind conditions on the curve, the "curve-running" efficiency of the sprinter, and so forth.

Table 1. Raw 200 m splits for zero wind and sea level conditions. Maximum velocity is 11.380 $\mathrm{m\,s^{-1}}$ at 65.066 m. Including a typical reaction time between 0.15–0.20 s would give a total time of 19.86–19.91 s.

d (m)	t (s)	v ($\mathrm{m\,s^{-1}}$)
10	1.762	8.445
20	2.847	9.866
30	3.820	10.633
40	4.740	11.059
50	5.634	11.280
60	6.517	11.370
70	7.396	11.372
80	8.277	11.313
90	9.165	11.210
100	10.062	11.078
110	10.971	10.923
120	11.892	10.813
130	12.820	10.736
140	13.756	10.617
150	14.705	10.468
160	15.668	10.297
170	16.648	10.110
180	17.647	9.912
190	18.666	9.705
200	19.708	9.492

A set of parameters that satisfy this criteria are

$$\left(f_0 = 6.0\ \mathrm{m\,s^{-2}};\ \sigma = 2.2\right), \qquad \left(f_1 = 4.83\ \mathrm{m\,s^{-2}};\ c = 0.24, \alpha = 0.323\ \mathrm{s^{-1}}\right),$$
$$A_\mathrm{d} = 0.00288\ \mathrm{m^2\,kg^{-1}};\ \xi = 0.015 \tag{8}$$

The associated splits are presented in Table 1. At zero wind and sea level, these produce an overall raw time of 19.708 s, with a 100 m split of 10.062 s. For a reaction time of about 0.15 s, this implies a race time of 19.86 s. Note the 150 m split is 14.705 s, or 14.86 s including reaction, consistent with the projected data.

It should be noted that these parameters are different than those selected for the 100 m analysis in ref. 1. The present choice does not change the correction estimates for the 100 m, but is significant for the 200 m. This issue is discussed in detail in Sect. 5.

There is a notorious lack of wind data for the first half of the 200 m dash. In fact, the wind gauge is only operated for the last 10 s of the race, from the time the first sprinter enters the straight. Hence, the available gauge data apply only to the last 85 m of the race. Until the IAAF institutes mandatory placement of wind gauges at the midpoint or top of the curve, the corrections can only be crude at best (this also ignores the fact that the wind speeds are doubtfully constant in the stadium).

Thus, two separate cases will be considered. The first assumes that the wind is entirely in the direction of the 100 m straight ($\theta = 0$ in (7)). This will provide for a varying head-to-tail wind around the curve (or tail-to-head, depending on its direction). Following this analysis, the effects of an arbitrary crosswind will be addressed.

Fig. 2. Velocity curves for the 200 m sprint in 19.709 s at sea level with a straight tail wind.

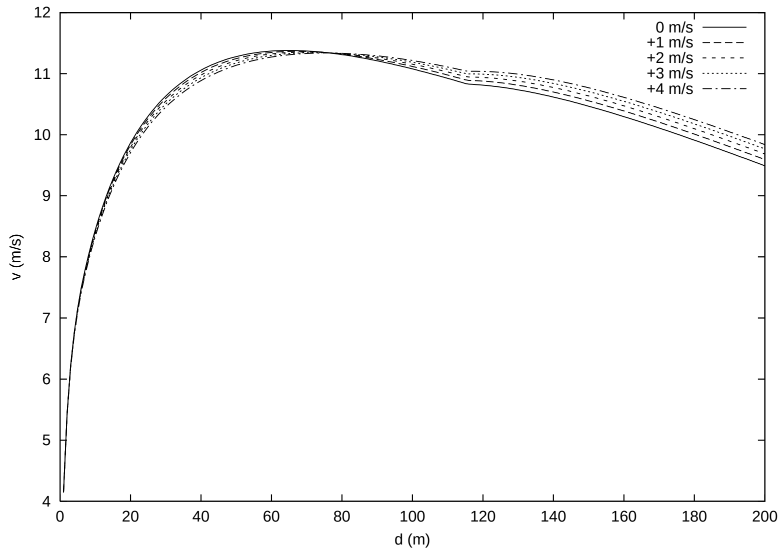


Table 2. Straight-wind correction $\Delta t = t_{\text{race}} - 19.708$ s estimates (s) for the Men's 200 m at selected altitudes.

Wind ($\mathrm{m\,s^{-1}}$)	0 (m)	500 (m)	1000 (m)	1500 (m)	2000 (m)	2500 (m)
−4.0	+0.371	+0.294	+0.221	+0.153	+0.089	+0.029
−3.0	+0.259	+0.189	+0.123	+0.061	+0.003	−0.051
−2.0	+0.160	+0.097	+0.037	−0.019	−0.072	−0.122
−1.0	+0.074	+0.016	−0.039	−0.090	−0.139	−0.184
0.0	—	−0.054	−0.104	−0.151	−0.196	−0.238
+1.0	−0.063	−0.112	−0.159	−0.203	−0.244	−0.283
+2.0	−0.114	−0.160	−0.204	−0.245	−0.284	−0.320
+3.0	−0.154	−0.198	−0.239	−0.278	−0.315	−0.350
+4.0	−0.183	−0.225	−0.265	−0.303	−0.337	−0.371

4.1. Straight winds, $\theta = 0$

Figures 2–4 show the velocity curves for the parameters in (8) for several wind speeds and altitudes, with the associated corrections in Table 2. The associated 100 m split corrections are given in Table 3. The zero wind altitude corrections are consistent with those for the 100 m [1,20], as should be expected. As these values suggest, the split times are not significantly affected by such wind conditions, showing variations of only several hundreds of a second for low-altitude runs. The overall 200 m corrections are quite striking in their magnitude. Although not a designation recognized by the IAAF, a "minimum altitude-assisted run" (one for which $H = 1000$ m) with no wind is corrected by almost the same amount as the legal wind limit ($+2\ \mathrm{m\,s^{-1}}$). If these figures are accurate, the resulting advantage raises many questions as to the legality of such conditions under the current IAAF regulations (see ref. 23). A wind of $+1.8\ \mathrm{m\,s^{-1}}$ in Mexico City (2250 m) would give an advantage of about 0.29 s, implying that Pietro Mennea's long-standing record of 19.72 s was probably closer to a 20.00 s run, consistent with his other personal best performances (see Sect. 7).

The most striking element of Figs. 2 and 3 is the "merge point" near 80 m, where the velocity curves intersect, effectively independent of the wind speed. An enlargement of the region shows that the curves

Fig. 3. Velocity curves for 200 m sprint in 19.709 s at sea level with a straight head wind.

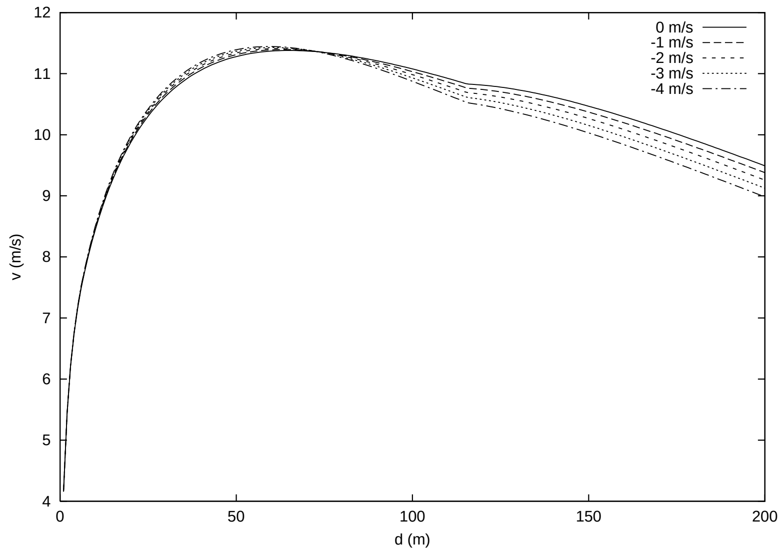


Table 3. Straight-wind 100 m split corrections $\Delta t = t_{\text{race}} - 10.062$ s estimates (s) for the Men's 200 m at selected altitudes.

Wind ($\mathrm{m\,s^{-1}}$)	0 (m)	500 (m)	1000 (m)	1500 (m)	2000 (m)	2500 (m)
−4.0	−0.036	−0.051	−0.066	−0.080	−0.092	−0.104
−3.0	−0.031	−0.046	−0.061	−0.075	−0.088	−0.101
−2.0	−0.023	−0.039	−0.054	−0.069	−0.082	−0.095
−1.0	−0.013	−0.030	−0.045	−0.060	−0.074	−0.087
0.0	—	−0.018	−0.034	−0.050	−0.064	−0.078
+1.0	+0.015	−0.003	−0.021	−0.037	−0.052	−0.067
+2.0	+0.033	+0.013	−0.005	−0.022	−0.038	−0.053
+3.0	+0.053	+0.033	+0.013	−0.005	−0.022	−0.038
+4.0	+0.076	+0.054	+0.033	−0.014	−0.004	−0.022

do not exactly overlap at one particular point, but this seeming convergence is interesting nonetheless. This serves to exemplify the relative independence of the sprinter's velocity curve in the initial stages of the race, and how the wind conditions down the straight contribute the bulk of the drag effects.

4.2. Crosswinds, $\theta \neq 0$

This section reveals the necessity of recording crosswind conditions in competition. If a wind w blows at an angle θ as described in Fig. 1, the resulting gauge reading will be $w\cos\theta$, i.e., the component of w in the direction of the 100 m straight. Hence, there can be a wide range of actual wind conditions for a single gauge reading. Table 4 and Fig. 5 demonstrate the predicted variability in correction estimates for wind conditions that produce a maximum legal wind reading of $+2.0\ \mathrm{m\,s^{-1}}$, including $+2.31\ \mathrm{m\,s^{-1}}$ (±30°), $+2.83\ \mathrm{m\,s^{-1}}$ (±45°), and $+4.0\ \mathrm{m\,s^{-1}}$ (±60°). As the overall wind speed increased, the assumption that the wind component perpendicular to the direction of motion is negligible may begin to break down, and so some of the presented corrections may overestimate the

Fig. 4. Velocity curves for 200 m sprint in 19.709 s showing altitude assistance only (zero wind).

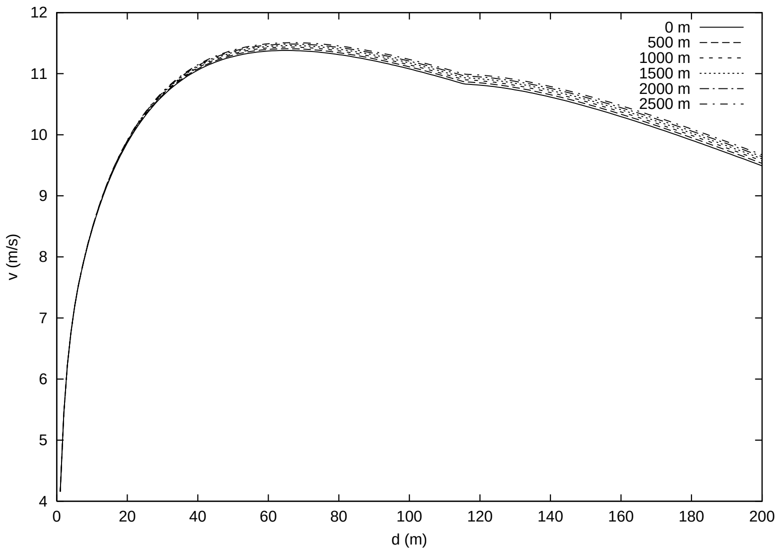


Table 4. Correction estimates (s) for crosswind in the Men's 200 m, yielding a wind-gauge reading of $+2.0\ \mathrm{m\,s^{-1}}$. The differential δ denotes the absolute difference between the extremal corrections.

Altitude (m)	+60 (°)	+45 (°)	+30 (°)	0 (°)	−30 (°)	−45 (°)	−60 (°)	δ
0	+0.183	+0.049	−0.023	−0.114	−0.197	−0.254	−0.342	0.525
1000	+0.059	−0.060	−0.123	−0.204	−0.278	−0.328	−0.406	0.465
2000	−0.052	−0.157	−0.213	−0.284	−0.349	−0.393	−0.463	0.411

true value.

At sea level, the difference between the maximum and minimum corrections considered is in excess of 0.5 s. This implies that times run with an "equal" wind may, in fact, differ by a significant amount. The altitude effects serve to diminish the corrections, bringing the differential δ down to under 0.4 s.

4.3. Influence of lane assignments

The athlete's lane assignment will explicitly influence the degree of wind assistance/resistance around the curve. The stagger required to account for the longer curve distance between lanes 1 and 8 is approximately 26.5 m, implying greatly different initial orientations with respect to the prevailing wind.

The choice of ξ used herein yields a performance of 19.760 s in lane 1, with a corresponding 19.651 s in lane 8 (to which the aforementioned correction factors apply). That is, an "equivalent" effort would be required to produce these two times (hence it is easier to run in the outer lanes, due to the wider curve). Although the exact effects of the curve on performance are unknown, this 0.1 s difference seems reasonable, and it should be pointed out that small variations in the value of ξ do not appreciably influence the resulting wind and altitude corrections.

Table 5 shows the correction estimates for the parameters used herein. So, if equal caliber sprinters race in lanes 1 and 8, their times will be equally separated via altitude effects alone, which is perfectly reasonable. However, once wind effects are considered, the 0.1 s gap can either be widened or closed. For a head wind of $+4.0\ \mathrm{m\,s^{-1}}$ at sea level, the lane 1 sprinter will clock 19.624 s, while his lane 8 competitor crosses the tape in 19.410 s (a difference of -0.214 s). Alternatively, for a head wind of

Fig. 5. Relative wind strengths felt by sprinters for varying crosswind angles.

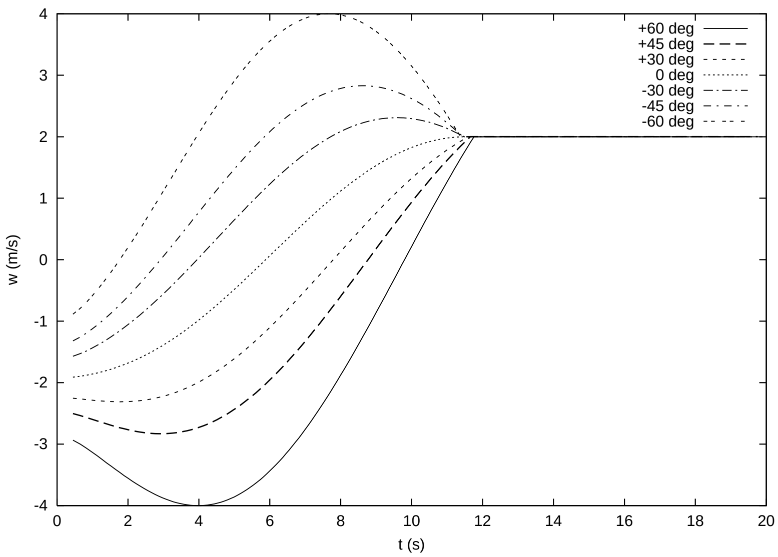


Table 5. Straight-wind correction estimates (in s) for lanes 1 and 8, for the Men's 200 m at selected altitudes.

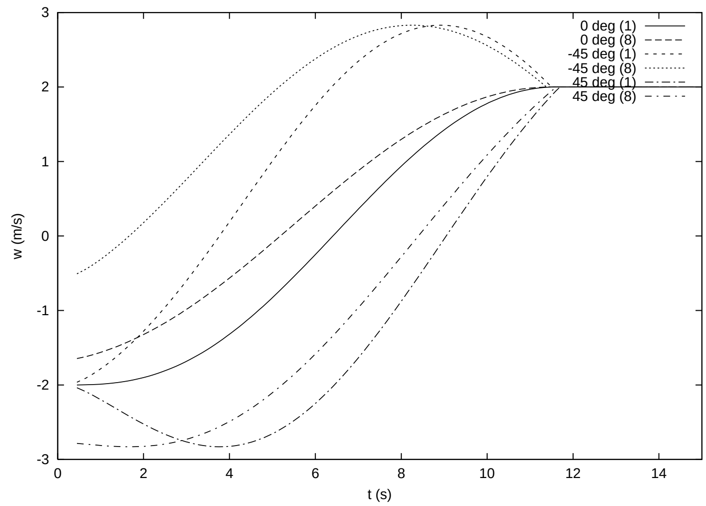
Wind ($\mathrm{m\,s^{-1}}$)	0 (m)	1000 (m)	2000 (m)
Lane 1			
−4.0	+0.334	+0.188	+0.060
−2.0	+0.141	+0.020	−0.087
0.0	—	−0.103	−0.195
+2.0	−0.091	−0.184	−0.266
+4.0	−0.136	−0.223	−0.300
Lane 8			
−4.0	+0.418	+0.262	+0.125
−2.0	+0.185	+0.058	−0.054
0.0	—	−0.104	−0.196
+2.0	−0.141	−0.228	−0.306
+4.0	−0.241	−0.316	−0.384

$-4.0\ \mathrm{m\,s^{-1}}$, the corresponding times will be 20.094 and 20.069 s, less than 0.03 s different! Altitude effects similarly influence the times, as the tables suggest (albeit to a lesser degree than the wind).

Crosswinds stand to further widen or narrow the gap in performances between the lanes. Although an exhaustive analysis is not offered at present, Fig. 5 is given to demonstrate the corresponding influence for crosswinds that produce a wind reading of $2.0\ \mathrm{m\,s^{-1}}$. As previously discussed, these results are severely hampered by a lack of wind data over the first half of the race, however, nonetheless they provide pause for thought. Figure 6 shows the variation between lanes 1 and 8, as discussed in the previous section.

It should be noted that the 0.1 s difference between lanes 1 and 8 predicted by the model is physically intuitive, but in fact most sprinters prefer lanes 4–6, due to the psychological influences of "seeing" their competition. The fact that the fastest performances tend to come from these lanes is not because

Fig. 6. Relative wind strengths felt by sprinters for varying crosswind angles in lanes 1 and 8 (lane assignment is indicated in parentheses).



they are easier to run in, but rather the top athletes are seeded from the center lanes out. Accordingly, if the fastest athletes are placed in the outer most lane, the resulting times could be up to 0.05 s faster!

5. The 200 m is not the 100 m

As previously noted, the parameters used in the 200 m simulation are different from those for 100 m sprinters in ref. 1

$$\begin{aligned} (f_0, \sigma) &= (6.10, 2.22) \\ (f_1, c, \alpha) &= (5.1, 0.038, 0.323) \\ A_\mathrm{d} &= 0.00288 \end{aligned} \tag{9}$$

The 50 m split profile for a 200 m simulation using these parameters is presented in Table 6, including the curve-dampening factor $\xi = 0.015$. This presents a generous 100 m split (faster than that of the 200 m counterpart), but the race is considerably worse from that point on, generating a final sub-par time of 20.631 s. Clearly, this is indicative that the 200 m race is not run in the same way as the 100 m race, which requires a maximum velocity earlier in the race to achieve faster overall splits (and final time).

In this case, the final 100 m times are not significantly different, although the 100 m sprinter is clearly the victor. In fact, thanks to a stronger acceleration, the 100 m sprinter is generally about 0.1 s faster for each 10 m split. The slower, conservative pick-up of the 200 m sprinter allows for greater energy to run a better second half of the race. Comparing the initial values of f_m for each simulation, the “200 m specialist” (8) exerts only 95% of the total effort of the “100 m specialist” (whose parameters are listed in (9)). A calculation of f_m (2) at $t = 10$ and 20 s reveals that the 100 m sprinter has depleted his reserves by 32% and 53%, respectively, while the 200 m sprinter depletes his reserves by 21% and 38%. In other words, the 200 m specialist maintains 10% more “energy” at 10 s, and 25% more at 20 s. The 100 m sprinter reaches maximum velocity at 60 m, contrasted to the 200 m sprinter’s 70 m maximum.

Notions of energy conservation in racing have been the subject of several past reviews [21, 22]. A racing strategy that has been proposed by several prominent sprint coaches is that the 100 m sprinter

Table 6. A (t) and (v) comparison of 100 and 200 m "sprinters" in a straight 100 m race ($\xi = 0.0$). The maximum velocity of a 100 m sprinter is 11.81 m s^{-1} (60.378 m), and the maximum velocity of a 200 m sprinter is 11.846 m s^{-1} (70.104 m).

	200 m		100 m	
d (m)	(t)	(v)	(t)	(v)
10	1.753	8.538	1.713	8.762
20	2.823	10.045	2.757	10.27
30	3.775	10.891	3.691	11.089
40	4.671	11.387	4.573	11.534
50	5.538	11.668	5.431	11.750
60	6.389	11.807	6.279	11.814
70	7.234	11.846	7.126	11.770
80	8.079	11.816	7.980	11.650
90	8.928	11.734	8.845	11.475
100	9.784	11.615	9.724	11.258

Table 7. The 200 m correction estimates for 100 m sprinter parameters.

Wind (m s^{-1})	0 (m)	1000 (m)	2000 (m)
−4.0	+0.471	+0.290	+0.130
−2.0	+0.202	+0.056	−0.074
0.0	—	−0.121	−0.228
+2.0	−0.141	−0.245	−0.338
+4.0	−0.226	−0.320	−0.404

must conserve his/her energy, through the first 50 m of the race, to have a strong second half. These figures could be interpreted to suggest that such a strategy is in theory possible, but does not necessarily allow for faster splits over 60 m.

Additionally, these data can help to quantify why many prominent 200 m sprinters are not successful 100 m candidates. Only two or three of the top 10 all-time 200 m sprinters have broken 10.00 s in the 100 m, and of those only two have broken 9.90 s. Perhaps the greatest 200 m sprinter in history, Michael Johnson, has a comparatively lackluster personal best in the 100 m. The greater speed endurance of the 200 m athlete allows for a longer maintenance of a higher velocity, but this is not reached in a short enough time to produce a world-class 100 m clocking.

5.1. Drag modification differences for 100 and 200 m specialists

In terms of wind and altitude assistance for these two sets of parameters, the corresponding 100 m corrections are virtually identical between the two (and again, consistent with the "accepted" figures). However, surprising differences arise when the race is extended to 200 m, as are indicated in Table 7. At sea level, the corrections differ by about 0.02 s, but increase for stronger winds and higher altitudes. While the differences are not large, they do indicate that the influence of drag modification in the longer sprints depends strongly on the velocity profile from 100–200 m, in particular the last 50 m or so. If the athlete is weaker toward the end of the race, the drag reduction can assist him more than for a sprinter who powers "smoothly" through the tape. This suggests the interesting conclusion that despite training

Table 8. World Record progression t_w (w) in the 200 m since 1968, showing corrected performances t_0.

Date	Athlete	t_w (w) (s; m s^{-1})	Venue	Altitude (m)	t_0
12 September 1968	John Carlos	19.92 (+1.9)	Echo Summit, Calif.	2250	20.22
16 October 1968	Tommie Smith	19.83 (+0.9)	Mexico City, Mexico	2250	20.09
12 September 1979	Pietro Mennea	19.72 (+1.8)	Mexico City, Mexico	2250	20.02
23 June 1996	Michael Johnson	19.66 (+1.7)	Atlanta, Ga.	350	19.74
01 August 1996	Michael Johnson	19.32 (+0.4)	Atlanta, Ga.	350	19.38

differences between 100 and 200 m specialists, the race is effectively won in the last 50 m! So, a true race between these distinct types of athletes really is a 150 m showdown (in the spirit of the failed match between sprinters Donovan Bailey and Michael Johnson in 1997, which was analyzed previously using an older incarnation of this model [10]).

6. Comparison to other correction figures

As previously mentioned, Behncke's 1994 paper [13] offers wind and altitude correction estimates for both the 100 and 200 m. For world class male sprinters, it was found that a $+2$ m s^{-1} (-2 m s^{-1}) wind would provide a 0.223 s advantage (0.255 s disadvantage) in the 200 m (accounting for track curvature). In contrast, the present study finds correction estimates of 0.112 and 0.160 s, respectively (Table 2), almost a factor of 2 different in each case. It should be noted that the reported correction for 100 m times under the same conditions are 0.135 and 0.156 s, respectively, which can be compared to 0.104 and 0.130 s from the model used herein (reported in ref. 1). Since the latter figures for the 100 m are generally accepted, it is assumed that Behncke's corresponding 200 m calculations are also overestimates. Frohlich [11] assumes a larger drag coefficient of $Cd = 0.9$, and obtains an even higher correction figure of -0.751 s ($+0.666$ s) for a $+2$ m s^{-1} (-2 m s^{-1}) wind. It is unclear whether or not track curvature and (or) a changing effective wind velocity were taken into account in this case.

For purely altitude-assisted runs, ref. 13 suggests that 200 m times can be improved by 0.084 s (1100 m) and 0.165 s (2200 m), as compared to 0.109 and 0.215 s for equivalent altitudes (lane 4) in this model. Thus, it is interesting to note that Behncke finds higher wind corrections and lower altitude corrections for 200 m races. Reference 11 offers a substantially higher correction figure of 0.401 s for 200 m races run at Mexico City (2250 m). It is suggested in ref. 13 that this altitude will provide a 0.94% advantage to 100 m times, or roughly 0.09 s [13]. The equivalent figure from ref. 1 would be about 0.07 s.

References 12 and 13 also address the effects of lane assignment and track curvature on sprint performances in the 200 m. It is shown in ref. 13 that successive outer lanes will provide a 0.009 s advantage, or an overall 0.063 s difference between lane 1 and 8, slightly lower than the 0.1 s estimate quoted in Sect. 4.3. The results of ref. 12 are conversely mild overestimates of the current figures, citing an advantage of 0.123 s between inner and outermost lanes. Comparing standard 200 m races with "straight" ones (no curved portion of the race), ref. 12 suggests that the discrepancy in race times is roughly 0.42 s, assuming the former is run on a curve of radius $R = 38$ m (roughly lane 2). The present model yields moderately higher figures of 0.59 s for lane 1, and 0.48 s for lane 8. Greene uses a top speed of 10 m s^{-1} on the curve to calculate the associated estimate, while this model yields top speeds of 11.34 m s^{-1} (lane 1) and 11.43 m s^{-1} (lane 8), which are much more consistent with actual speeds achieved by world class sprinters.

Table 9. Top 10 low-altitude ($h < 1000$ m) rankings since 1968, ordered by corrected performances.

t_0	$t_w(w)$	Athlete	Venue (altitude)	Date
19.72	20.01 (−3.4)	Michael Johnson	Tokyo (95)	27 Aug 91
19.73	19.73 (−0.2)	Michael Marsh	Barcelona (95)	05 Aug 92
19.74	19.68 (+0.4)	Frank Fredericks	Atlanta (350)	01 Aug 96
19.75	19.80 (−0.9)	Carl Lewis	Los Angeles (100)	08 Aug 84
19.80	20.06 (−3.1)	Michael Johnson	Tokyo (95)	27 Aug 91
19.82	19.77 (+0.6)	Michael Johnson	Stockholm (20)	08 Jul 96
19.82	19.61 (+4.0)	Leroy Burrell	College Station (300)	19 May 90
19.83	19.79 (+0.5)	Michael Johnson	Göteborg (0)	11 Aug 95
19.83	19.88 (−0.9)	Michael Johnson	Barcelona (95)	20 Sep 91
19.85	19.85 (−0.9)	Ato Boldon	Lausanne (600)	03 Jul 96

7. Correction of world rankings

From the advent of required electronic timing until the summer of 1996, the World Record in the 200 m had been set exclusively at high-altitude venues ($h > 2000$ m). An application of the correction figures discussed herein demonstrates that *many* exceptional performances were overlooked in the interim. Since one cannot ascertain the wind conditions or directions around the turn, the following discussion is again based on the assumption that the wind was purely straight (no crosswinds) and unvarying across the stadium. The corrections also assume that the performance was run in lane 4.

Table 8 shows the World Record progression between 1968 and 1996, along with the associated wind and altitude data, and the resulting correction. As a comparison, Table 9 contains the best low-altitude performances (corrected and uncorrected) over the same interval. Note that the three World Records, set prior to Michael Johnson's 1996 races, all correct to over 20.00 s races in still conditions at sea level, are certainly not record caliber! These adjusted marks are consistent with the athlete's other corrected top performances (see ref. 23 for a more comprehensive discussion of these corrections as applied to world rankings).

Thus, a scan of the record books reveals that there are several 200 m performances that surpassed the marks of Smith after 1968, and Mennea after 1979. Table 9 shows the top-ranked corrected performances between 1968 and 1996 (note that there have been some additions since that time). Carl Lewis, one of the greatest sprinters of the 1980s, could have posted a 19.75 s record as early as 1984. Interestingly enough, Michael Marsh's 19.73 s time at the 1992 Olympics in Barcelona remains untouched by the correction, a result of the headwind-resistance and altitude-assistance combination.

An anomaly of note is the 19.61 s ($+4$ m s^{-1}) clocking of Leroy Burrell. Although his performance adjusts to 19.82 s, it should be noted that Burrell was a 100 m specialist, whose next best 200 m performance barely broke the 20 s barrier. This could be an example of the phenomenon discussed in Sect. 5, i.e., greater adjustments for "weaker" sprinters near the end of the race. Furthermore, the wind gauge reading is actually listed as >4 m s^{-1} [24], so there is some uncertainty as to the validity of these data.

Whether it be corrected world lists, or the official ones, the proliferation of Michael Johnson's marks cannot be ignored. Perhaps the most impressive performances listed in the Table are his feats at the 1991 World Championships in Tokyo. Extremely strong headwinds did not allow his official times to dip below 20 s, yet the corrected marks suggest that these were quite spectacular performances! It would not be until 1996 that Michael Johnson would make his definitive mark on the record books. In fact, this provides a suitable segue into the closing section.

Table 10. Raw theoretical 10 m splits of Michael Johnson's 19.313 s World Record race. $w = 0.41\ \mathrm{m\,s^{-1}}$ at $\theta = -20°$ (gauge reading $+0.39\ \mathrm{m\,s^{-1}}$); $H = 350$ m; and maximum velocity $11.582\ \mathrm{m\,s^{-1}}$ (71.993 m). Official reaction is $+0.161$ s. $\Delta_{10} = t_i - t_{i-1}$ is the interval duration.

d (m)	Split (s)	v ($\mathrm{m\,s^{-1}}$)	Δ_{10}
10	1.766	8.426	1.766
20	2.852	9.872	1.086
30	3.823	10.673	0.971
40	4.738	11.138	0.915
50	5.625	11.402	0.887
60	6.496	11.535	0.871
70	7.361	11.581	0.865
80	8.225	11.566	0.864
90	9.091	11.506	0.866
100	9.964	11.416	0.873
110	10.844	11.301	0.880
120	11.733	11.222	0.889
130	12.626	11.172	0.893
140	13.524	11.084	0.898
150	14.431	10.969	0.907
160	15.348	10.834	0.917
170	16.277	10.684	0.929
180	17.220	10.523	0.943
190	18.178	10.354	0.958
200	19.152	10.180	0.974

8. The 200 m World Record: 19.32 s

Although the main focus of this paper was not to model exact splits that functionality remains as an attractive feature. There is probably no better 200 m race to simulate than Michael Johnson's astounding World Record run of 19.32 s from the 1996 Atlanta Olympic Games. The only known split data for this race are those obtained through a frame-by-frame video replay analysis [25]. The choice of parameters $(f_1 = 4.78, c = 0.020, \alpha = 0.323)$; $(f_0 = 6.00, \sigma = 2.2)$; $\xi = 0.012$; $w = +0.41\ \mathrm{m\,s^{-1}}$; and $\theta = -20°$ reproduces the 100 m split and final race time. The simulation wind gauge reads $+0.3\,9\ \mathrm{m\,s^{-1}}$, which would be rounded up to the reported $+0.4\ \mathrm{m\,s^{-1}}$. The altitude of Atlanta is roughly 350 m. The value of ξ is lower than in previous sections, as the assumption is made that Michael Johnson can run curves more efficiently than other sprinters.

The simulation results are presented in Table 10, and are compared to the reported results in Table 11. The difference between the two is about 0.04 s, with the noted exception at 146.42 m. This mismatch is most likely due to a clerical error in ref. 25, a methodological error, or a combination of both.

At sea level in zero-wind conditions, the time would translate to $19.219 + 0.161 = 19.380$ s (always assuming a 0.161 s reaction). Had it been run in Mexico City, the model suggests a 19.172 s in still wind, and 19.099 s with a straight $+2\ \mathrm{m\,s^{-1}}$ tail wind. Furthermore, letting $\xi \to 0$, at sea level the "straight track" equivalent of his 10.13 s split would theoretically be 9.909 s.

Table 12 contains the corresponding theoretical 50 and 100 m interval analysis. Note the outstanding

Table 11. Comparison with recorded data from ref. 25. Rounding procedure is IAAF standard.

d (m)	Recorded (s)	Model (s)	Rounded	Difference
90	9.29	9.253	9.26	−0.03
100	10.13	10.125	13.13	0.00
110	11.00	11.005	11.01	+0.01
131.14	12.93	12.889	12.89	−0.04
140.28	13.75	13.710	13.71	−0.04
146.42	14.57	14.266	14.27	−0.30
158.56	15.42	15.376	15.38	−0.06
167.70	16.27	16.224	16.23	−0.04
176.84	17.12	17.082	17.09	−0.03
185.98	17.97	17.953	17.96	−0.01
200	19.32	19.313	19.32	0.00

Table 12. Raw 50 and 100 m interval analysis of Michael Johnson's 200 m World Record.

50 m		100 m	
Interval (m)	Split (s)	Interval (m)	Split (s)
0–50	5.625	0–100	9.964
50–100	4.339	**40–140**	**8.786**
100–150	4.467	50–150	8.806
150–200	4.721	100–200	9.188

split of 8.786 s between 40–140 m. Although such "running-start" performances are rarely clocked, Carl Lewis was timed in 8.86 s for his final leg in the 4×100 m relay at the 1987 World Championships [26]. If this simulation is accurate, this constitutes one of the fastest 100 m intervals run by *any* athlete in history. The corresponding simulated 150 m split would be 14.592 s, officially reported as 14.60 s.

Surely, if these results are correct, Michael Johnson's run was not only the fastest 200 m ever, but arguably one of the greatest athletic feats of all-time!

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