matters arising

Tornado forum

RECENTLY the proposal was made that motor traffic has contributed significantly to the sixfold increase in incidence of tornadoes in the USA in the past forty years.[1] The authors saw the vorticity introduced into the atmosphere by traffic driving on the right as favouring the generation of cyclonic tornadoes, and they were encouraged in this hypothesis by an increase in the proportion of cyclonic to anticyclonic tornadoes, and also by the low incidence of tornadoes reported on Saturdays, when traffic would be lower and more unidirectional (away from large cities).

The suggestion has provoked many responses and to publish them all would have occupied more space than we could allot. So we print below abridged versions of some of the communications received, followed by a reply from the authors.

[1] Isaacs, J. D., Stork, J. W., Goldstein, D. B., and Wick, G. L., *Nature*, **253**, 254–255 (1975).

A MOTOR vehicle or any other projectile in air produces vortices in its wake, but no net vorticity. If there are anticyclonic vortices along edges of the highway, as shown in Fig. 1 of Isaacs *et al.*, their vorticity must be balanced by cyclonic vorticity in the median strip.

The width of a highway is small compared to a cloud, and a significant updraft entraining the vortices produced by motor vehicles would realise no net contribution from that source. The main atmospheric phenomena produced by cars are turbulence, and gaseous and particulate combustion products along the highway, dissipating and diffusing downwind.

The low incidence of tornadoes on Saturdays perhaps reflects some unfortunate vagaries in reporting. Or, conceivably, changes in the atmospheric radiation budget and aerosol content induced by weekend factory closings and lowered air pollution produce changes in static stability and cloud particle development.

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WE believe that the mechanism for vorticity generation and accumulation in the atmosphere proposed by Isaacs *et al.* is based on misconceptions about the nature of vorticity. The atmosphere contains background vorticity arising from the rotation of the Earth and relative vorticity from weather disturbances and boundary effects, including moving vehicles. In fact the background vorticity can be ignored to high accuracy in the dynamics of flow around vehicles, since Coriolis effects are minute. The following argument depends, however, mainly on kinematical results, which are exact.

We begin by considering the generation of vorticity by a single moving vehicle. Absolute vorticity can be generated in a homogeneous fluid only at boundary surfaces moving relative to the fluid[1], and so is generated at the sides, top and bottom of the vehicle, at its wheels and at the ground in its neighbourhood. Once generated it is advected with the air stream into the vehicle's wake. The vortex filaments of the resulting relative vorticity vector field ω must either form closed loops or terminate at a boundary rotating relative to the Earth; and on this basis we can distinguish two constituents in the relative vorticity generated at a moving vehicle:

(1) When the vehicle moves in a straight line, closed vortex loops are shed continuously into its wake. These profoundly affect local levels of vorticity close behind the vehicle, but have no effect whatever either on the circulation round a contour enclosing the wake, or on the bulk integral

$$\int_V \omega \mathrm{d}V$$

over a volume V including the wake and the neighbourhood of the vehicle, because each vortex filament is closed. (None of these facts is changed by the presence within V of more vehicles whether driving on the right or on the left.)

(2) Vorticity having a net vertical component is generated when a vehicle turns, at a rate proportional to minus the rate of change of angular velocity of the vehicle about the vertical; see equation (1). There is an additional net horizontal component associated with the rotation of the wheels, which need not concern us further.

It is immediately clear that randomly varying vehicle movements can have no systematic gross effect over a large area as claimed by Isaacs *et al.* The vehicles could, however, produce localised concentrations of vorticity (changing sign over length scales of a few metres) the significance of which will depend very much on persistence and hence on inter-diffusion rates. We shall discuss this question further elsewhere, but remark here that order-of-magnitude estimates based on plausible levels of turbulence suggest persistence times of minutes rather than hours, and vortices of dust devil rather than tornado scale.

If, as an opposite extreme, a large number of vehicles were to be driven simultaneously in fast clockwise circles, there would indeed temporarily be a cyclonic (that is, anticlockwise) contribution to the bulk vorticity integral. But this can be shown to be associated entirely with the air below vehicle rooftop level or, more precisely, below a plane surface s lying just above all the vehicles. When summed over the vast bulk of the atmosphere lying above s, the total component of vorticity normal to s caused by the vehicles is, and must remain, exactly zero (see equation (2) below). This is a consequence of the simple fact that each vehicle-generated vortex filament passing upward through s must go back down through s at another point, possibly terminating on a moving surface such as the underside of the same vehicle.

In summary, neither mechanism (1) nor (2) can plausibly be connected with the generation of tornadoes, which takes place high above the ground and which involves air motions coherent over length scales of kilometres.

Isaacs *et al.* stated that cyclonic vorticity "is generated by the torque between the two opposing streams of traffic", and this led to their view that it is better to drive on the left than the right of the road. Unfortunately torque does not determine the generation of vorticity, either locally or globally. Although doubling the separation of two traffic streams may approximately double the torque (to say nothing of the far larger contribution from unidirectional traffic on widely-separated highways) it has absolutely no effect on the net generation of vorticity. The vorticity due to the traffic streams is, to an excellent approximation, the sum of the contributions produced at the surface of each vehicle, locally redistributed by advection and diffusion; and any effects on the bulk vorticity integral have nothing to do with the separation of traffic streams, nor with left as against right hand drive.

The basic mathematical fact underlying our discussion is the solenoidal property of ω: since ω is the curl of a velocity