**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 favouning 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.


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 downward.

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, 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 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 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 interdiffusion 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)). 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 movement 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-separatetd 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 or right hand drive.

The basic mathematical fact underlying our discussion is the solenoidal property of ω: since ω is the curl of a velocity field, υ·ω is identically zero. It follows that

\[ \int_V \omega \cdot dV = \int_S \frac{\partial}{\partial \sigma} \left( x \cdot \omega \right) dS = \int_S x \cdot (\omega \cdot n) dS \]

where V is a suitable piece of the atmosphere, partially bounded by the surface S, comprising the ground and the surfaces of stationary and moving objects (vehicles, their wheels, aeroplanes) which are envisaged as the source of the contribution ω to the relative vorticity, itself
supposed confined within \( V \). From this identity it may readily be shown that

\[
\int_V \omega dV = -2 \sum_{i=1}^n \Omega_i (V)
\]

where \( \Omega_i (V) \) is the angular velocity of the \( r \)-th moving body, and \( V, \) its volume. We here use the fact, fundamental to the vorticity generation mechanism, that the no slip condition applies at all parts of the surface \( S \).

Further, if all the moving objects lie below a plane surface \( S \) then, if \( \omega_3 \) is the component of \( \omega \) normal to \( S \) and \( \nu \) is the part of \( \omega \) above \( S \),

\[
\int_S \omega_3 dS = \int_V \nu \cdot dV = 0
\]

Hence, by integration with respect to \( x_n \),

\[
\int_V \omega dV = 0
\]

The results (1) and (2) are both exact, even for an atmosphere in which the motion is baroclinic, compressible, and turbulent.

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ISAACS ET AL. assert that the opposing streams of traffic on a road induce a net cyclonic vorticity in the atmosphere. Because vorticity diffuses exponentially slowly at large distances from a source, however, this is not so.

If the opposing traffic streams are modelled by infinite plates a distance \( D \) apart, then the resulting mean flow field at any finite time after the motion begins is of the form shown in Fig. 1. The detailed behaviour of the mean velocity profile near the plates is unimportant.

Although the motion near the plates is turbulent in general, any far-field disturbance must propagate normal to the plates by the action of molecular diffusion, and so the mean velocity decays exponentially as \( y \rightarrow \infty \). Thus, integrating the mean vorticity \( \Omega = \Omega_3 \) with respect to \( y \), we find that the total vorticity per unit distance along the plates in the region \( |y| > D/2 \) is finite and equal to \( 2\Omega_3 \) whereas the total vorticity in \( |y| < D/2 \) is equal to \(-2\Omega_3 \), where \( \Omega_3 \) is the speed of each plate. Thus the cyclonic vorticity in the region between the plates is just balanced by the anticyclonic vorticity outside the plates. Alternatively, we see that the net circulation around a closed contour (as shown by the dotted line in Fig. 1) goes to zero as the \( y \) dimension of the contour increases. This is because the cyclonic torque induced by the plates is opposed by the inertia of the fluid at infinity, which is at rest.

This result implies that although cyclonic vorticity is generated between the streams of traffic, there is no net generation of vorticity, because an equal amount of anticyclonic vorticity is also induced. It would seem therefore that, according to the hypothesis of Isaacs et al., either both cyclonic and anticyclonic tornadoes ought to be equally probable, or no tornadoes ought to be generated, depending on whether the air is not, or is mixed horizontally in the process of tornado generation.

On the other hand, Isaacs et al. do give some strong circumstantial evidence for the connection between cyclonic tornadoes and traffic-induced vorticity. Their hypothesis can perhaps still be retained if the second ingredient involved in the generation of tornadoes, namely convection, is included. Any vorticity induced by traffic is initially confined to a layer a couple of metres deep near the ground. To produce a tornado, this vorticity must be preferentially advected vertically. Such motions are found in convection, which is an anisotropic process where horizontal mixing is suppressed. Moreover, road pavement in general absorbs more solar radiation than does the surrounding terrain and so the road is expected to be a stronger source of convection than the surrounding terrain. (The cars themselves also act as a local heat source.) Convection therefore ought to occur preferentially from the road. Because the cyclonic vorticity (of mean strength \( 2\Omega_3/D \)) is concentrated over the road while the anticyclonic vorticity is diffused on each side of the road, it would appear that the convection leads to the preferential advection of cyclonic vorticity into the troposphere, as required by Isaacs et al. That is, cyclonic tornadoes can be produced because roads are sources of both cyclonic vorticity and convection.

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A calculation is indicated, though not shown, by Isaacs et al., purporting to prove that motor vehicle traffic contributes significantly to the atmospheric vorticity over the USA and thereby leads to a more homogeneous cyclonic troposphere and consequently to changes in the broad scale spatial and temporal distribution and frequency of tornadoes. In the following I have attempted to repeat the calculation, with results substantially different from those of the authors.

A typical round trip is taken to be a straight line of length \( L \), a straight line return and a U-turn at each end, with a separation between lanes of width \( d \). If the average force exerted backwards by the wheels on the road is \( F \), then the net anticyclonic angular momentum added to the earth, located at the centroid of the path, is \( 2FLdV \), where \( V \) is the automobile speed, with nominally equal contributions coming from the straight legs and the U-turns. We assume the force \( F \) to be the air drag of the vehicle, given by

\[
F = \rho aC_D V^2/2
\]

where \( \rho \) is the air density, \( a \) is the cross-sectional area of the vehicle, and \( C_D \) is the drag coefficient, taken to be 0.5. Since the speed while making the U-turn is likely to be much less than that on the straight legs, we ignore those contributions, and the average torque produced by the vehicle is then

\[
T = FD = \rho aC_D V^2d/2
\]

Isaacs et al. assume that \( 2 \times 10^6 \) automobiles are on the road in the USA at any time, and that the contributions to torque from autos and trucks are equal. Using these figures, and assuming a mean cross-sectional area of \( 1 \text{m}^2 \), \( V = 20 \text{m/s} \), the lane spacing \( d = 20 \text{m} \), and \( \rho = 1.3 \text{ kg m}^{-3} \), we obtain a net torque pro-
duction of $3.2 \times 10^4$ kg m$^2$ s$^{-2}$. In this
calculation, the difference in direction between the torques produced in different
parts of the USA is ignored, which amounts to assuming the cosine of angles
smaller than $\sim 20^\circ$ to be unity.

The angular momentum, $M$, of a
rotating body is the second radial
donom of its vorticity

$$M = \int \zeta dm,$$

where $\zeta$ is the vertical component of
vorticity and $dm$ is the mass differential.

Over the USA during most seasons, the
authors envisage would occur if all the
to the vertical component of the Earth's
vorticity, $f \approx 10^{-4}$ s$^{-1}$. Thus the angular
momentum of the atmosphere of the USA is roughly

$$M = \rho g A f r^2/2,$$

where $\rho$ is the mean surface pressure,
$g$ is the acceleration of gravity, $A$ is the
area of the USA, and $r$ is the mean radius,

$$M = 1.6 \times 10^{10}$ kg m$^2$s$^{-1}. Thus it would seem that the motor vehicle torque would have to
reach for $10^4$ s, about 3 Myr, to show a noticeable effect. The natural

turnover time of angular momentum in the atmosphere is of order days or weeks,

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Rotation sense is given for too few
tornadoes to be of significance; the big
surprise is that any anticyclonic tornadoes whatever are reported. "Motor vehicles
ignoring the only man-made source of non-
random vorticity we know", the authors
say. Perhaps they have never seen two
railway trains pass at full speed, or noted
the action of exhaust fans and rooftop
ventilators.

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Isacks*, Stork and Wick* reply—

Opposing streams of traffic in the USA

anticyclonic torques on the solid
Earth and, from action and reaction,

competing cyclic torques on the
atmosphere. These torques tend to slow
down the Earth's rotation and to increase
the cyclonic rotation of the local atmos-
phere in its conservation of angular
momentum.

We agree with Kessler1, Morton et al.3
and Mantoon4 that there is zero net
vorticity in the total atmosphere caused
by traffic. Our original discussion was
based on vorticity rather than angular
momentum. We were in error in not
recognising that a discussion of the process from a consideration of vorticity
is much less direct than from a considera-
tion of angular momentum. Angular
momentum is a more fundamental
quantity in the formation of strongly
rotating storms.

There can be little doubt that US au-
motive traffic introduces cyclonic angular
momentum into the local atmosphere,

which can participate in the formation of
tornadoes. To illustrate how this occurs,
consider, for example, this idea: if you set fluid in a bowl into circulation by periods

immersing your hands and moving them
past one another in straight lines always
in the same relative direction but in any
orientation and location, the fluid will gain
angular momentum. Yet for this fluid the
no-slip condition at the boundaries
requires zero net vorticity. The boundary
vorticity does not preclude the formation of
a vortex when the fluid is allowed to
flow through an orifice in the bottom of
the bowl. The important points are that
angular momentum can be introduced by
linear motions in this way, and that it can
participate in a vortex while the net
vorticity remains zero.

The apparent paradox of automobile-
generated angular momentum with zero
vorticity is probably resolved through
several mechanisms in the atmosphere.

As in the example of the bowl, the
boundary vorticity in the atmosphere
may propagate and act outside the area of


convergence, as we originally proposed. The resolution may not be unrelated to our recent observation alongside a highway bearing heavy traffic that anticyclonic filaments of small-scale rotation are embedded in large-scale cyclonic rotation.

At any rate, our calculations of the torque and resulting angular momentum agree with those of Lilly, but are more conservative by a factor of about eight. We do not consider, as he did, that the torque on the atmosphere be applied to the entire air mass over the USA as though the atmosphere were a solid body. Rather this torque must exert its influence locally, and in areas consonant with those involved in the convective processes of a tornadic storm. Furthermore, if variations in local vehicle concentrations of two orders of magnitude are taken into account, our calculations show that vehicle-produced torque, over reasonable periods of time, can produce angular momentum of the same order or greater than the natural background (see Fig. 1).

The angular momentum introduced annually by vehicles is sufficient to account for that present in ~ 10^9 plant tornadoes. (A total of ~ 600 including all sizes are actually reported per year.)

Court’s point that the centre of tornado occurrence has moved westward makes it even more impressive that the centre of tornado intensity, which is what we reported, has increasingly occupied the eastern sections of the USA. The obvious inference here is that the more intense tornadoes have been increasingly found in the east in support of our original thesis.

We agree that too few observations of the rotational sense of tornadoes have been reported to make these data highly significant. A χ^2 test based on these data shows, however, a statistically significant shift from anticyclonic to cyclonic tornadoes over the 24-yr period, and thus these data support our hypothesis. The fact that anticyclonic tornadoes exist at all is important in showing that local effects other than planetary rotation can be significant for the formation of tornadoes. One of these local effects could be vehicle-generated cyclonic angular momentum.

Darkow’s raises an interesting point in attributing the weekly periodicity of the tornado data to periodicity in newspaper reporting. The possibility of reporting peculiarities being the cause has also concerned us. Before our initial publication, one of us contacted the Administrator of the National Oceanic and Atmospheric Administration, who was certain that weekend reporting was adequate or even intensified because of increased exposure to more people at weekends. In addition, since the data on the tornado tape we acquired from the National Severe Storms Forecast Center (NSSFC) are listed by source, we were able to separate out those that were identified as press clipping data (33%). The remaining data showed an even stronger weekly periodicity than reported for the total. These remaining data are considered to be the most reliable data by NSSFC.

As a further check we had plotted tornado injuries, damage, tornado days, path area and sums of f-scale numbers by day of week. We thought that tornadoes of sufficient significance to require the reporting of these parameters would not be subject to such reporting vagaries as might affect the reporting of lesser tornadoes. In every case Saturday was low, thus increasing our confidence in the validity of the findings.

Weekend changes in the production of factory wastes could conceivably influence the static stability and cloud-particle development as suggested by Kessler. It is difficult, however, to see why this phenomenon would have its effect only on Saturday and not on Sunday. Presumably a factory that is closed on Saturday will remain so on most of Sunday. As a further check we have obtained a tape of thunderstorm data from NSSFC and analysed it for weekly periodicity. We found none. Thus it seems that the periodicity in tornado occurrence is not dependent on convective storm periodicity but more probably on the periodicity of input of that unique and essential ingredient of tornadoes—angular momentum.

Referring again to Fig. 1, the planetary angular momentum scales by the fourth or fifth power of the radius of the area involved in convection, depending on the type of convergence, while energy scales only as the second power of the radius. Thus a strong argument can be made that, if energy limits the population of strongly rotating convective storms of the magnitude of hurricanes (which seems to be the case), storms of the magnitude of tornadoes are comparatively deficient in planetary angular momentum, as related to energy by at least three orders of magnitude. The fact that most thunderstorms do not involve tornadoes seems to support this statement. This argues that angular momentum, rather than energy, limits the population of tornadoes, and that any input of cyclonic angular momentum increases their incidence, as we have proposed.

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